SECTION 5.0
HYDROLOGIC CHANGE

5.1 INTRODUCTION

The Acme WAU comprises nearly 90 square kilometers of valley-bottom and mountainous topography that drain into a 13-km reach of the South Fork Nooksack River. Elevations in the WAU range from 75 to 940 m; the median elevation of the WAU is approximately 225 m. The valley bottom of the South Fork comprises approximately 40% of the total WAU area and consists mostly of floodplain and terrace deposits.

From a hydrologic perspective, the boundaries of the Acme WAU present unique problems associated with hydrologic analysis of peakflows. For example, most of the flow in the South Fork Nooksack River is derived from a drainage area that is much larger and of higher elevation than the Acme WAU. Waters from upriver sources thus enter the southern end of the WAU, travel along the valley, and exit the northern end of the WAU where the South Fork joins with the main Nooksack River. Any effects on the flow regime of the South Fork Nooksack River from human activities "up-drainage" of the Acme WAU were outside the scope of this analysis and were not considered in any of the hydrologic evaluations.

The South Fork Nooksack River and its broad floodplain effectively dissect the WAU into two mountainous areas. Relatively steep forested slopes occur on both sides of the valley and geomorphically confine the floodplain and gentle slopes of the broad valley floor of the South Fork system. These slopes east and west of the valley bottom provide relatively distinct hydrologic units herein identified as the Eastern SubWAU and the Western SubWAU, respectively (Figure 5-1). These subWAUs, comprised of lands generally above the 125-m elevation contour, are used primarily for commercial forest operations.

Area-elevation relationships indicate that the Western SubWAU has a greater proportion of higher elevation lands than the Eastern SubWAU (Figure 5-2). Both SubWAUs contain numerous and generally parallel tributaries that exit onto the South Fork valley bottom. For hydrologic analysis of peak flows associated with forest harvesting, each subWAU was analyzed separately. Furthermore, the Jones Creek Watershed in the southwestern portion of the Western SubWAU was separately analyzed for peakflow changes because a relatively high proportion of its drainage area is within the characteristic rain-on-snow zone of western Washington.

Because of local and regional concerns regarding the potential effects of forest harvesting on peakflows from rain-on-snow events, a Level 2 analysis was conducted for the Eastern SubWAU, the Western SubWAU, and the Jones Creek Watershed. A Level 2 analysis was expected to provide a more accurate characterization of harvesting effects upon peakflows than is attainable under the more general Level 1 analysis (page C-11 of Hydrologic Change Module, WFPB 1994).

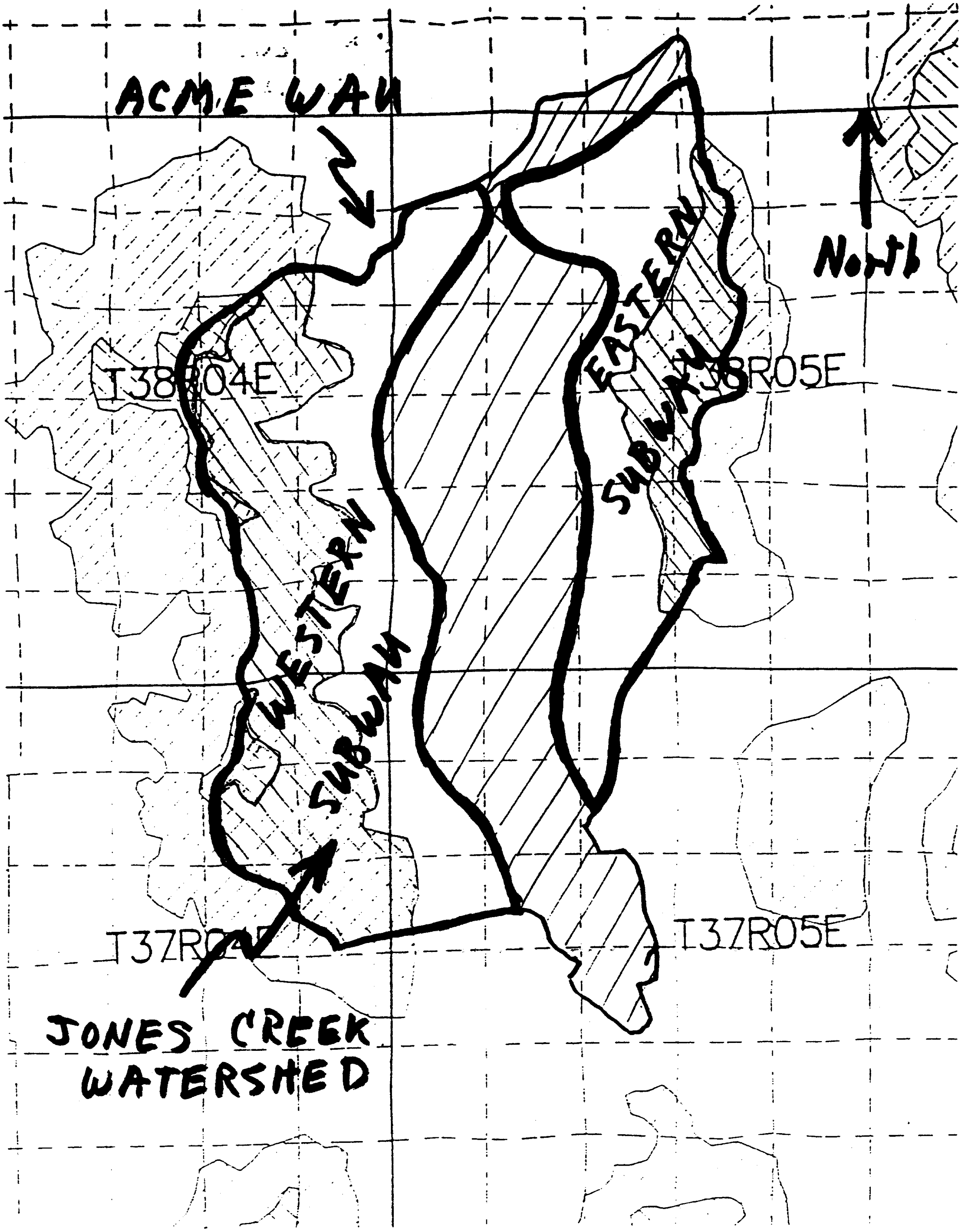


Figure 5-1 Location of Eastern SubWAU, Western SubWAU, and Jones Creek Watershed within the Acme WAU.

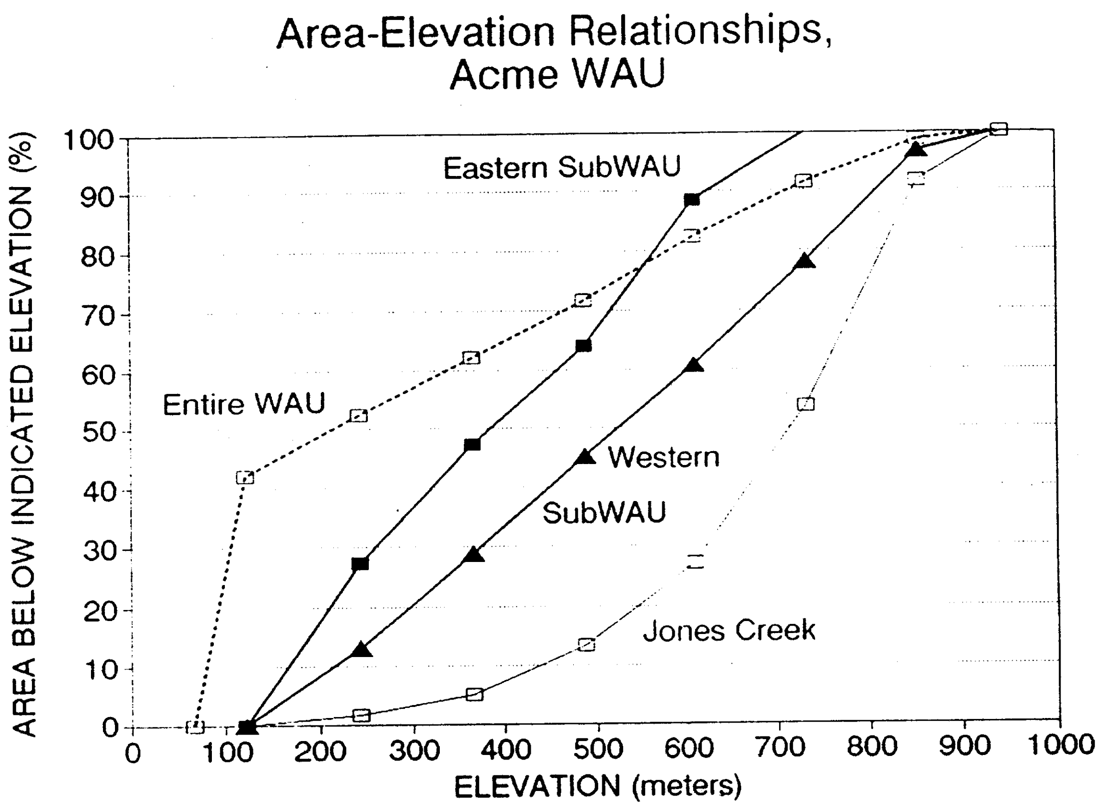


Figure 5-2 **Area elevation relationships for the Acme WAU and other areas within the WAU.**

While the following analysis attempts to address the critical questions indicated on page C-4 of the Hydrologic Change Module (WFPB 1994), the primary emphasis is directed at potential effects of forest harvesting upon the hydrology of rain-on snow events. A major assumption of the Hydrologic Change Module is:

> The greatest likelihood for causing significant, long-term cumulative effects on public resources via alteration of forest hydrologic processes is through increases in peak flows attributable to the influence of timber harvest on winter snow accumulation and melt rates during rain-on-snow (ROS) events.

In addition to rain-on-snow considerations, stream crossing culverts were evaluated to determine whether they had sufficient capacity to pass highflows. Existing hydraulic capacities were compared to estimated peakflows from regional equations.

5.2 RAIN-ON-SNOW SIMULATIONS

Analyses of rain-on-snow peakflows were undertaken for the Eastern SubWAU, Western SubWAU, and Jones Creek Watershed to assess the effects of forest cover. Each of the three analysis areas were further divided into four elevation zones where snow accumulation, snowmelt, rainfall, and resultant peakflow hydrographs were separately characterized.

From inspection of precipitation records for the Nooksack Hatchery Weather Station located 15 km north of the Acme WAU, the five largest storms of record over a 15-year period (1976-1990) were selected for analysis. Although the general recurrence intervals of these storms is likely to range between approximately 3 and 16 years, several of the selected storms were of major proportions from a regional perspective. Over a 4-day period associated with each storm, hourly data from the Nooksack Hatchery were used to provide representative time series of hourly precipitation intensities for use in peakflow assessments (Figure 5-3). These time series of hourly precipitation intensities enabled the development of estimated rainfall amounts, over time, for various elevation zones within each of the subWAUs and the Jones Creek Watershed.

Precipitation records were augmented with corresponding time series of air temperature and windspeed data from the SEATAC Weather Station near Seattle. This supporting data was needed to allow simulation of snowmelt processes. Although each storm had a unique temporal distribution of precipitation amounts, temperature regimes, and windspeeds, the occurrence of warm temperatures and high winds generally coincided with periods of heavy rainfall that is characteristic of rain-on-snow events. A detailed discussion of hydrologic processes during periods of rain-on-snow, the effects of forest harvesting, and the simulation methods employed for these analyses are provided in Appendix 5-1 (Beschta, R.L., 1995, Rain-on-Snow Hydrologic Analysis: Acme Watershed Administrative Unit).

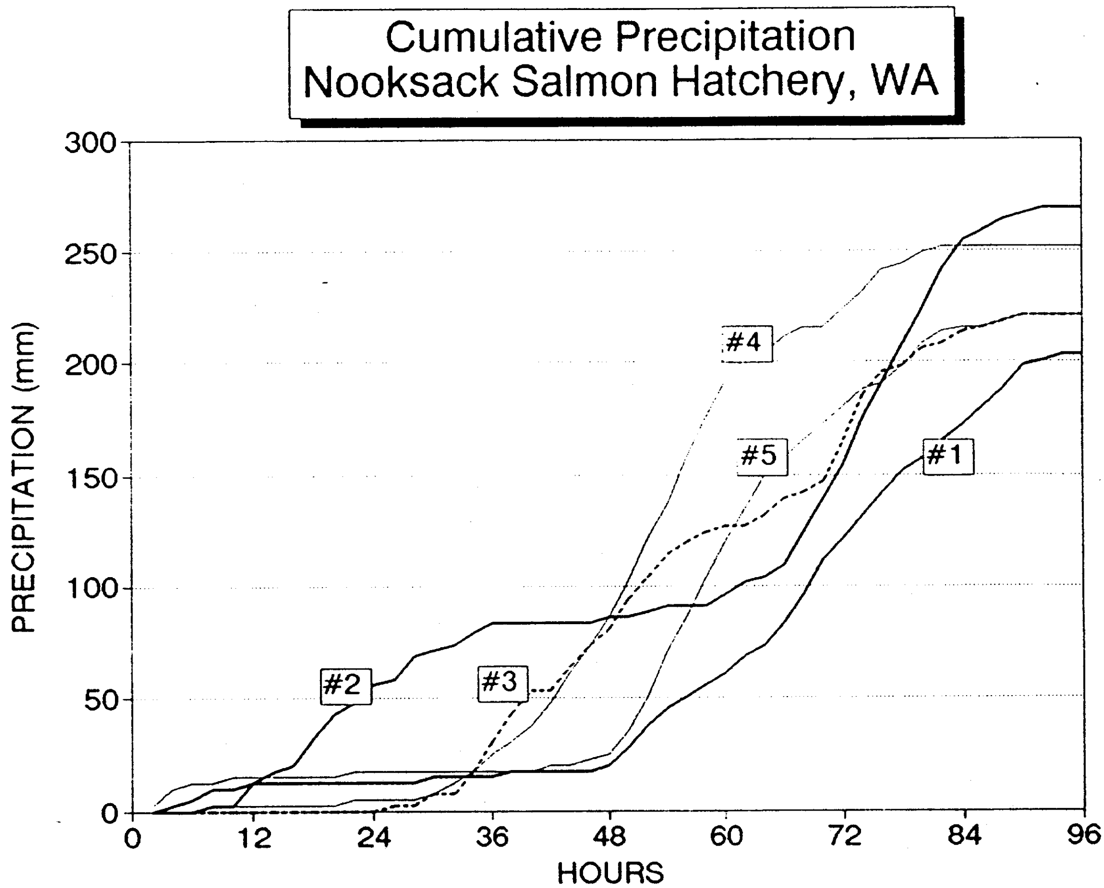


Figure 5-3 Cumulative storm precipitation for Storms #1 through #5, Nooksack Hatchery Weather Station.

Snowmelt rates were calculated bihourly utilizing information on snowpack water equivalents, meteorological information (i.e., precipitation, temperature, and windspeed), and snowmelt equations developed by the U.S. Army Corps of Engineers (1956). Hydrographs were generated for each storm using rainfall and snowmelt outputs as inputs to an Antecedent Precipitation Index (API) simulation model (Fedora and Beschta 1989). The API model provided the analytical basis for converting bihourly volumes of rainfall and snowmelt into peakflow hydrographs.

Three general forest cover conditions were simulated for each analysis area: (1) Fully Forested, whereby a forest cover of hydrologically mature vegetation (trees >25 years of age) was assumed to occur, (2) Existing Conditions, whereby the relative effects of existing forest age classes were evaluated, and (3) Entirely Clearcut, whereby a forest cover of hydrologically immature vegetation (i.e., ≤10-years of age) was assumed. The first and third situations represent the potential range of cover conditions that might influence peakflows during rain-on-snow events.

For the Fully Forested conditions, pre-storm snowpack water equivalents were estimated for each elevation zone based on a relationship between water equivalent and elevation. The relationship was derived from January 1 snowpack data for 27 snow course sites within 100 km of the confluence of the Nooksack Forks near Deming.

For Entirely Clearcut conditions, the snowpack water equivalent expected at a given elevation for forested conditions was increased an additional 38 mm (1.5 in). This incremental increase in snowpack water equivalent was based on snowmelt lysimeter research in the northwest Cascades (Connelly and Cundy 1992). A 38 mm increment exceeds measured differences between the amounts in an opening versus those under a forest canopy for approximately 80 percent of the rain-on-snow events reported by Connelly and Cundy (1992). Thus, this incremental adjustment was chosen to represent above-average harvesting effects.

For the peakflow simulations of Existing Conditions, the aerial extent of various forest age classes and a "hydrologic recovery" relationship were utilized to prorate the relative flow contributions from harvested and forested areas. The objective of these three analyses was to assess the probable effects of forest harvesting upon rain-on-snow peakflows in the Acme WAU.

5.3 SIMULATION RESULTS AND DISCUSSION

Results of the rain-on-snow simulations for Fully Forested conditions indicate a range of peakflows for the five storms. Simulated peakflows for the Eastern SubWAU, Western SubWAU, and Jones Creek Watershed averaged 1.03 cubic meters per second per square kilometer ($m^3s^{-1}km^{-2}$) (range = 0.86-1.25), 1.06 $m^3s^{-1}km^{-2}$ (range = 0.87-1.27), and 1.24 $m^3s^{-1}km^{-2}$ (range = 0.98-1.48), respectively.

The relative magnitude of peakflow responses associated with complete forest removal (i.e., clearcut conditions) increased directly with the proportion of watershed area within the transient snow zone (i.e., terrain generally above 500 m in elevation). For example, the Eastern SubWAU had only 33% of its area above the 500 m elevation whereas the Western SubWAU had 53% and the Jones Creek Watershed had 86% above this elevation. Increases in rain-on-snow peakflows associated with Entirely Clearcut assumptions for the Eastern SubWAU, the Western SubWAU, and the Jones Creek Watershed were 11, 20, and 26%, respectively (Figure 5-4).

The results of the peakflow simulations for the Entirely Clearcut conditions, when compared with measured flows from gaged watersheds in western Washington, can also be used to assess relative changes in flow frequency. Peakflow data from two watersheds, i.e., Lake Creek and Skookum Creek, were utilized for this analysis; the period of record for each of these gages is approximately 20 years. Annual peakflow data from these watersheds were used to develop a common "discharge vs recurrence interval" relationship (Figure 5-5). Utilizing this relationship and the rain-on-snow simulation results, the magnitude of a 10-year peakflow for clearcut conditions would be increased to approximately that of a 14-, 20-, and 24-year event for the Eastern SubWAU, the Western SubWAU, and the Jones Creek Watershed, respectively (Figure 5-5). Since recent clearcuts represent relatively small proportions of these watershed areas, general increased flows of this magnitude are not expected under current conditions.

The proportion of area occupied by young forest age classes (Figure 5-6) represents an important variable with regard to rain-on-snow effects associated with timber harvesting. Following harvesting, the establishment and growth of trees begins to reduce the potential for accelerated rain-on-snow melt in clearcut openings. As the height and canopy cover of establishing forest vegetation increases, the potential for increased snowpack accumulation and accelerated snowmelt are decreased. Although little "hydrologic recovery" is expected for the first 10 years following harvest, a transition to fully forested conditions develops rapidly over the next 15 years. For forest stands 25 years of age or greater, they are expected to function hydrologically in a manner similar to that of a mature forest.

The Eastern SubWAU, Western SubWAU, and Jones Creek Watershed have approximately one-third, or less, of their area occupied by forest age classes less than 25 years (see Table 5-1). As of late 1994, 16 to 23% of the SubWAUs were occupied by forest stands $\leq$10 years of age. Thus peakflow increases associated with "Existing Condition" simulations should be considerably less than those shown for Entirely Clearcut conditions. Simulations indicate that rain-on-snow peakflows associated with Existing Conditions represent an increase of only 3 to 6% above that indicated for Fully Forested conditions (Figure 5-4)

Comparing estimated increases of 3 to 6% with the discharge vs recurrence interval relationship for the Lake Creek and Skookum Creek Watersheds (Figure 5-5) indicates

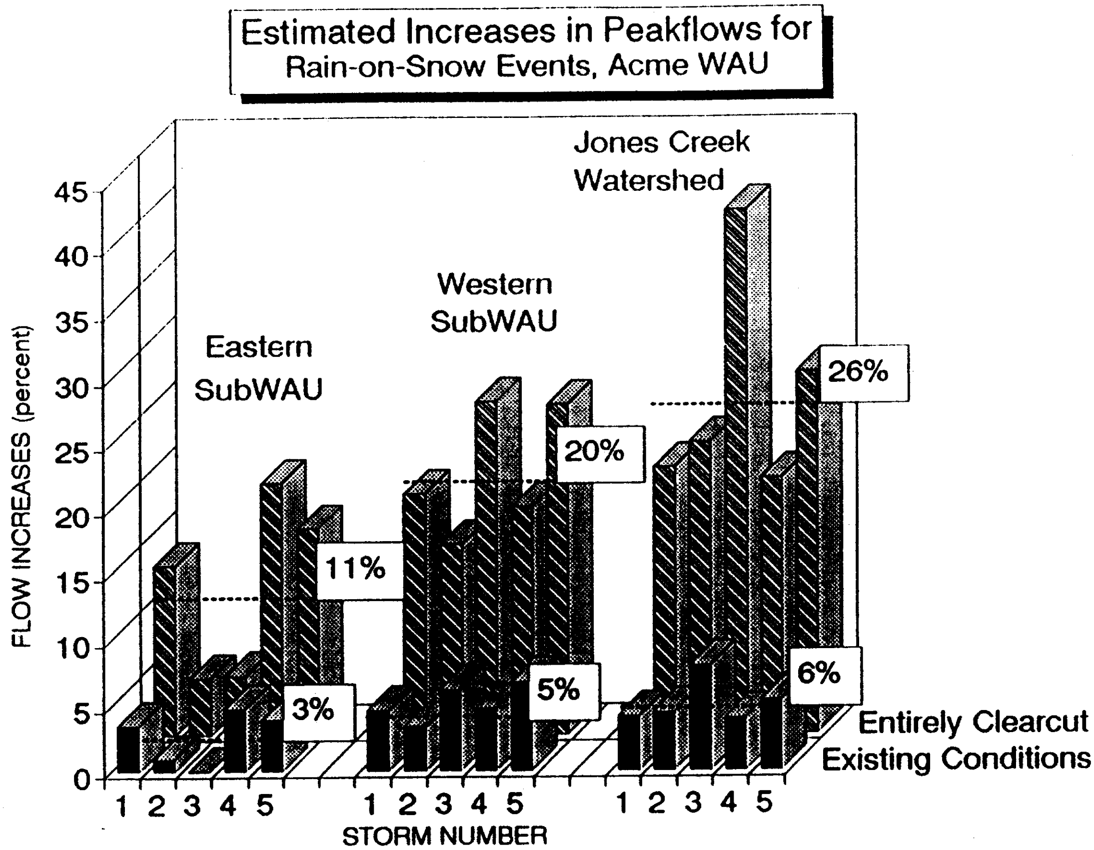


Figure 5-4 Projected increases in rain-on-snow peakflows comparing Existing Conditions and Entirely Clearcut conditions to Fully Forested conditions for selected areas within the Acme WAU. (See text for additional discussion).

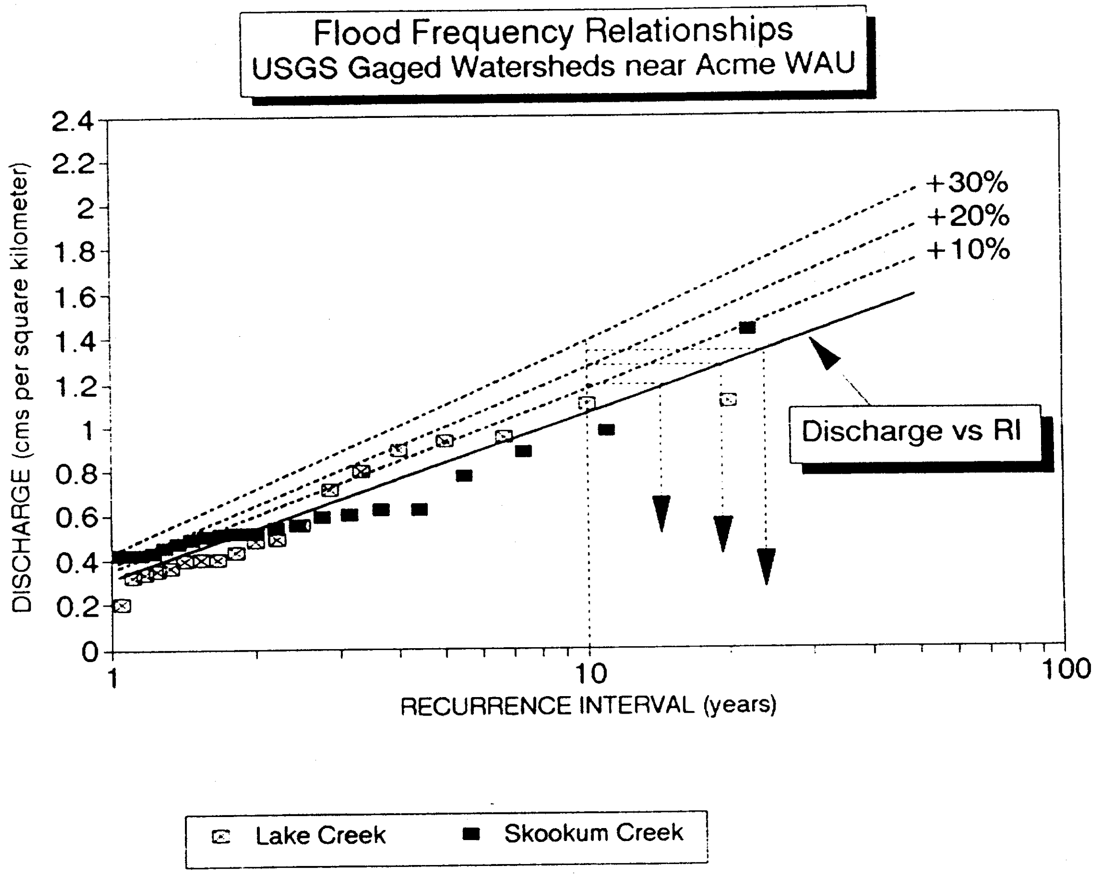


Figure 5-5 **Relationship of peak discharge vs. recurrence interval (RI) for Lake Creek and Skookum Creek, western Washington.**

Table 5-1 Percent of area in indicated forest age classes for portions of the Acme WAU as of 1994 (Note: Because age classes were obtained largely from interpretation of aerial photo imagery with some in-the-field verification, the exact age-class distribution of younger stands is not known. However, given the general level of modeling capability for rain-on-snow simulations, a more refined estimate of age-class distributions is not warranted).

	Percent of Area		
Forest Age Class (years)	Eastern SubWAU	Western SubWAU	Jones Ck. Watershed
0-10	22	16	23
11-26	13	21	0
27+	65	63	77

that these flow additions would increase the magnitude of a 10 year event to that of approximately a 11- to 12-year event (Note: A single average relationship was developed from the two gages. This average relationship is likely to more reasonably represent a regional flow-frequency relationship than would be afforded by the use of single gage). Given the wide range in annual peakflows experienced by mountain streams (the coefficient of variation in annual peakflows is nearly ±20% for the South Fork Nooksack River), and considering the potential for inaccuracies in meteorological estimates, simulation processes, and measured streamflows, a simulated 3 to 6% increase in peakflows for Existing Conditions would be exceptionally difficult to detect for any tributary streams within the Acme WAU. In addition, given the steep gradients and coarse substrates typical of channels in the Eastern and Western SubWAUs, and the importance of hillslope mass wasting processes in affecting stream channels, a 3 to 6% increase in peakflows is not expected to be a significant factor causing channel instabilities within the SubWAUs. However, if unconstrained stream reaches have previously become destabilized via landslides, dam-break floods, harvesting along streambanks, road drainage, or some other mechanism, increased flows may contribute to continuing unstable conditions.

The large natural variability of hydrologic processes, particularly those associated with large storm events, makes it difficult to develop definitive conclusions regarding how specific forest management practices affect runoff patterns or the stability of hillslopes and stream systems. However, several direct and indirect effects may potentially be associated with the additional snowmelt water from watershed areas occupied by young forest age classes (i.e., ≤25 years). For shallow soils on steep slopes, an increase in the amount of moisture available to watershed soils during large storms (e.g., a 11-26% increase in local peakflows were simulated for clearcut conditions) could contribute to a reduction in the factor of safety because of increased pore pressures. For deep-seated types of mass soil movements, the combined effects of reduced transpiration loss following forest harvesting and incremental increases in soil water during large storms might also augment the downslope movement of soil and weathered materials. In other instances, road drainage may be affected. For example, a 11 to 26% increase in peakflows from clearcut areas may be of sufficient magnitude to require increased culvert sizing at some stream crossings.

The potential for increases in water availability and peakflows to affect slope erosion process and channel stability are most likely to occur within or close to a harvest unit. Farther downstream, any increases in flow from a headwater watershed would become less significant.

5.4 CONCLUSIONS FROM RAIN-ON-SNOW SIMULATIONS

The Level 2 analysis of rain-on-snow hydrology for large winter storms associated with the Acme WAU indicates the following:

- During rain-on-snow conditions, rainfall provides the major source of moisture available to forest soils and stream systems.

- Depending upon location within the WAU, an 11 to 26% average increase in peakflows was projected for clearcut conditions. For slopes of marginal rain-on-snow stability, increased amounts of moisture delivered to the soils during rain-on-snow conditions as a result of clearcut harvesting may contribute to local slope instability and increased landslide frequency. This additional water should be considered with other onsite factors, such as the routing of water by road drainage systems and the loss of root strength following harvesting or burning, in assessing the relative stability of specific slopes.

- For areas that currently have, or will have in the future, a high percentage of area in younger age classes (i.e., ≤25-years old), an increased design capacity of approximately 10 and 20% for the Eastern and Western SubWAUs, respectively, should be considered for culverts and other drainage structures. For the Jones Creek Watershed, increased design capacities of 25% are recommended.

- The relative increase in rain-on-snow peakflows associated with simulations of clearcut harvesting (this analysis) are considerably smaller in magnitude than the regional increases projected by the Department of Natural Resources (1991).

- Subdrainages within the Acme WAU currently have approximately 23-37% of their area in forest age classes ≤25-years old. Rain-on-snow simulations for five large storm events indicates that accelerated snowmelt associated with current watershed conditions could potentially increase peakflows by an average of 3 to 6%.

- Based on a frequency analysis of annual peakflows for two gaged watersheds, a 3 to 6% increase in peakflows would increase the magnitude of a 10-year event to that of a 12-year event, or less.

- An approximate 3 to 6% average increase in peakflows during rain-on-snow conditions indicates that flow increases within the Acme Subwaus are unlikely to be a major cause of initiating channel instability. However, where unconstrained channel reaches have become impacted by other events (landslides, dam-break floods, etc.) flow increases may contribute to maintaining an unstable condition.

5.5 CAPACITY ANALYSIS OF STREAM CHANNELS AND CROSSING STRUCTURES

In interpreting the results the hydrologic simulations, an important question is whether peakflow increases will exceed the capacity of stream channels and road crossings structures, such as bridges and culverts. Evaluating the capacity of channels and culverts involves the use of standard hydraulic equations that predict the flow depth for a given flow rate and the local channel conditions (e.g. channel/culvert shape, slope, and roughness). Flow depths were analyzed at five channel locations downstream of west-side sub-basins (Section 5.5.1), including two at public road bridges. Flow capacities were also analyzed at 19 culvert locations in the WAU (Section 5.5.2)

5.5.1 Capacities of Small Channels and Bridges

At five channel sites, a capacity analysis was undertaken to determine whether rain-on-snow enhanced peakflows would exceed channel or bridge capacity. Three of the sites are located on Jones Creek because the potential for rain-on-snow increases are relatively large (26% average for completely clearcut conditions), and numerous public and private structures (roads, school, homes) are located on the alluvial fan area (WCPD 1992). The two other cross-section sites were located on Hardscrabble and Sygitowicz Creeks, due to vulnerable structures (houses and bridges) and the history of capacity problems at these locations (WCPD 1992).

More specific descriptions of each cross-section site and reasons for their locations are provided below:

Lower Jones is a cross-section within the diked channel about 100 m (~300 feet) downstream of the Turkington Road bridge. This site was located where overbank flows would naturally trend toward the Acme school.

Jones bridge cross-section is located closely upstream (~20 m) from the Turkington Road bridge. The channel is narrow and constrained by rip-rapped banks and high flows could potentially overflow the bridge.

Jones canyon cross-section is located in the narrow canyon about 300 m (1000') upstream of the Turkington bridge. Hillslopes on both sides are very steep and unstable and landslides from this area could send substantial sediment downstream. This cross-section site was chosen to determine whether peakflow increases would aggravate toe-slope undercutting.

Hardscrabble cross-section is located on Hardscrabble Creek approximately 50 m upstream from several structures (River Farm) located near the channel. Although the road crossing is hardened to allow overflow during storm events, buildings could be affected by overbank flows.

Sygitowicz bridge cross-section is located at the bridge at Hillside Road to evaluate the potential for overtopping during peakflows.

Other tributaries were not analyzed, either because less structural resources were at risk (e.g. Standard, McCarty and Falls Creeks) or the potential flow increase was less (e.g. Tinling Creek in the eastern sub-WAU). It is assumed that changes in flow levels in unanalyzed sites would be comparable, and potential damage less severe. No sites on the South Fork Nooksack River were analyzed because most of the drainage area is upstream of the Acme WAU and peakflow changes were not analyzed in this process.

Once channel cross-sections were surveyed in the field, flow levels were projected using a computer program that calculates open-channel flow conditions (Grant et al. 1992). Channel roughness at each location was accounted for using a Mannings "n" value based on the prevalent bed particle size. Flow levels were determined for peakflow rates from five different rain-on-snow situations, including the five-storm averages for full forest cover ("Ave FF" in Table 5-2), existing cover ("Ave EC") and completely clearcut conditions ("Ave CC"). The fourth and fifth flow rates were from simulation of Storm #4, which produced the largest flows of the five storms simulated. The Storm #4 flows reflect forested and completely clearcut cover conditions ("S4 FF" and "S4 CC", respectively). Comparing the flows from the two Storm #4 flows illustrates changes during a "worst storm with total clearcut" situation. All peakflows were determined from the rain-on-snow simulations for Jones Creek. Peakflows for Sygitowicz and Hardscrabble Creeks were extrapolated from Jones Creek simulations, adjusting for basin size and the existing hydrologic immaturity level for that particular basin (Table 5-2). Flow depths at the deepest part of the channel cross-section (italics in Table 5-2) were used for comparison between cover scenarios.

For existing forest cover, depths were slightly higher (1-3 cm, or 0.4-1.2") than for fully forested watershed conditions (Table 5-2). For the completely clearcut scenarios, depths were elevated by 6-10 cm (2-4"), illustrating the maximum potential response to forest cover removal from logging or wildfire. Cross-section diagrams (Figure 5-7 a-e.) illustrate the differences between scenarios at each site, though the vertical scale was exaggerated (varies between sites). Flow heights for the "Ave CC" and "S4 FF" are not shown on the figures to avoid crowding, since all lines would be relatively close together.

Not surprisingly, the smallest differences in flow height occurred at sites where the channel is relatively wide (e.g. Lower Jones and Hardscrabble), which allows increased flows to spread laterally as the depth increases. Flow depths at the highest predicted flow rate (i.e. S4 CC) are still 1-2 m below upper streambanks at all sites, suggesting that the hazard of channel overtopping is minimal, unless cross-sections change substantially. At the sites with bridges (Jones and Sygitowicz), flow heights are well below the bridge levels (Figure 5-7 e). Flows at the Jones canyon site remain well within the armored lower channel, reducing the possibility that undercutting of adjacent toe slopes will be increased.

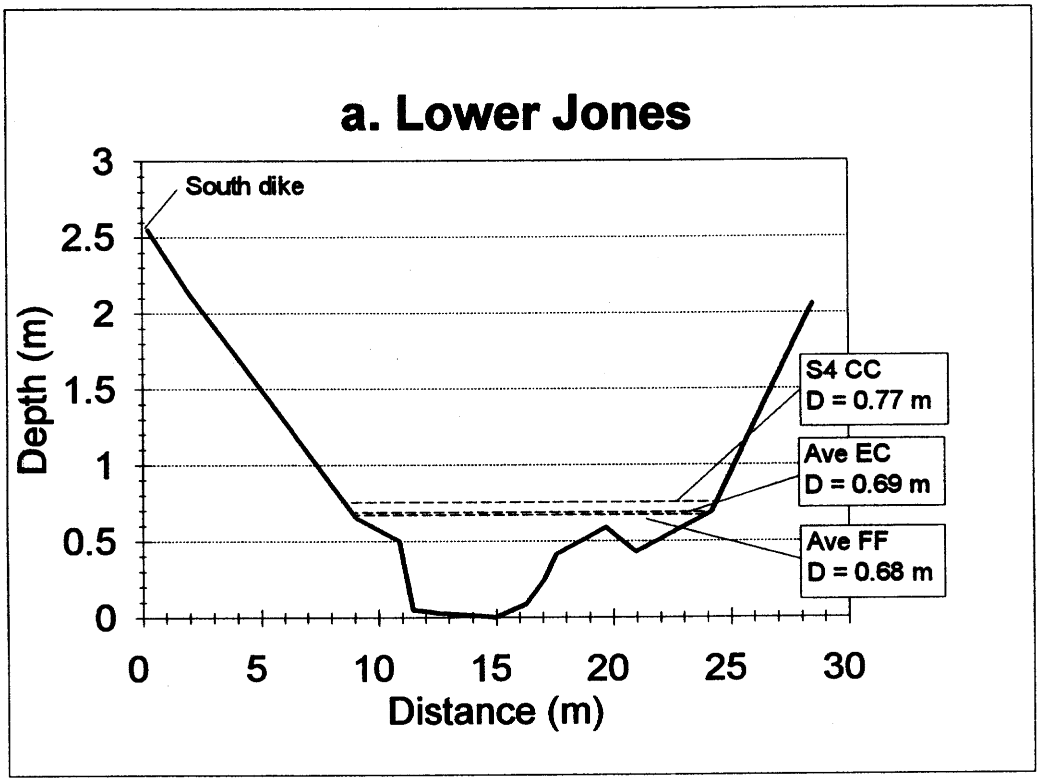
The scale of flow depth changes are relatively small, suggesting that harvest enhancement of rain-on-snow peakflows is at most a minor component of past alluvial fan problems. Most documented damage at alluvial fans in the Acme WAU have occurred during or immediately after debris flows or other massive sediment inputs (WCPD 1992). An observation of "flooding" was reported on Jones Creek near the Turkington Bridge in 1990, but involved bed aggradation estimated at four feet (1.2

Table 5-2 Peakflow rates and depths estimated from hydraulic analysis of cross-section sites in the Acme WAU.

Channel site	Drng. area (km^2)	Total HI[1] (%)	Ave FF	Ave EC	Ave CC	S4 FF	S4 CC
			Storm/cover scenario[2] flow (m^3/s) / *depth* (m)				
Lower Jones	5.69	23	7.1	7.5	8.9	8.4	10.2
			0.68	*0.69*	*0.74*	*0.72*	*0.77*
Jones bridge	5.69	23	7.1	7.5	8.9	8.4	10.2
			0.83	*0.85*	*0.93*	*0.90*	*0.98*
Jones canyon	5.69	23	7.1	7.5	8.9	8.4	10.2
			0.83	*0.85*	*0.92*	*0.90*	*0.97*
Hard-scrabble	2.13	12	2.6	2.8	3.3	3.2	3.8
			0.43	*0.44*	*0.47*	*0.46*	*0.50*
Sygitowicz bridge	5.47	32	6.8	7.2	8.5	8.1	9.8
			0.73	*0.76*	*0.82*	*0.80*	*0.88*

1 - Total Hydrologic Immaturity (1994) = % hydrologically immature (0-10 years) plus 1/2 the percentage that is partially mature (10-25 years).

2 - Average (Ave) storms are the average of all five simulated. Storm #4 (S4) rates are for the single storm (#4) that produced the greatest peakflow. Cover scenarios are fully forested (FF), existing conditions (EC) and completely clearcut (CC).



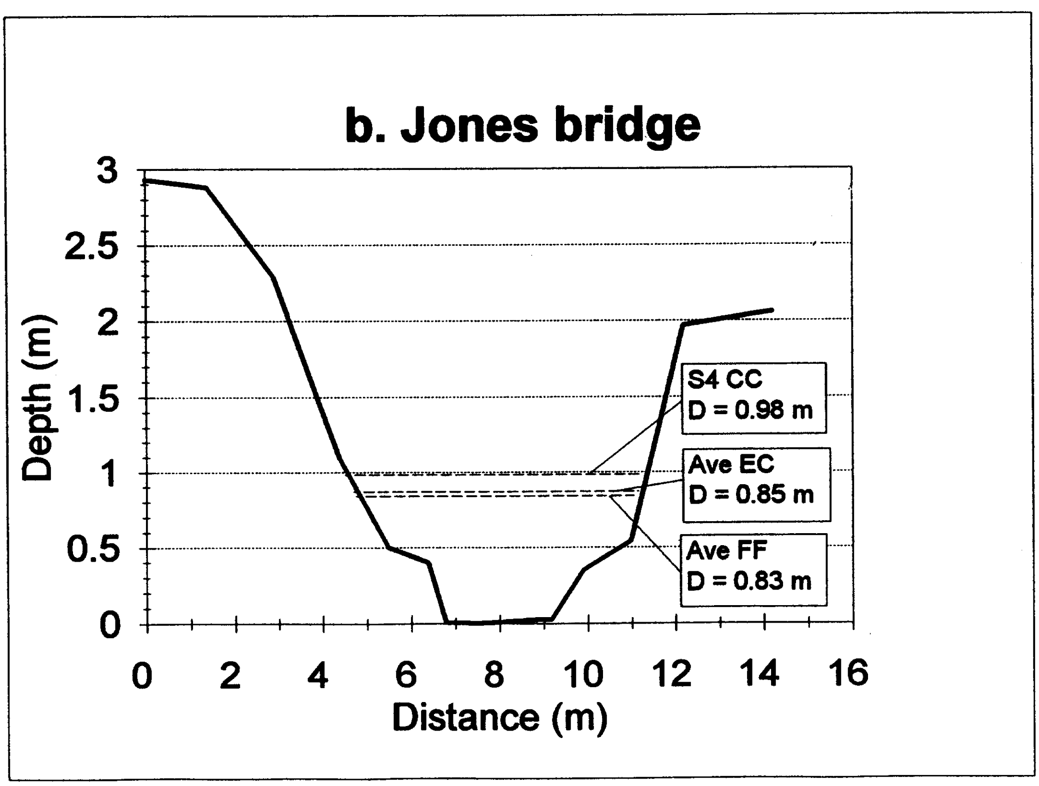
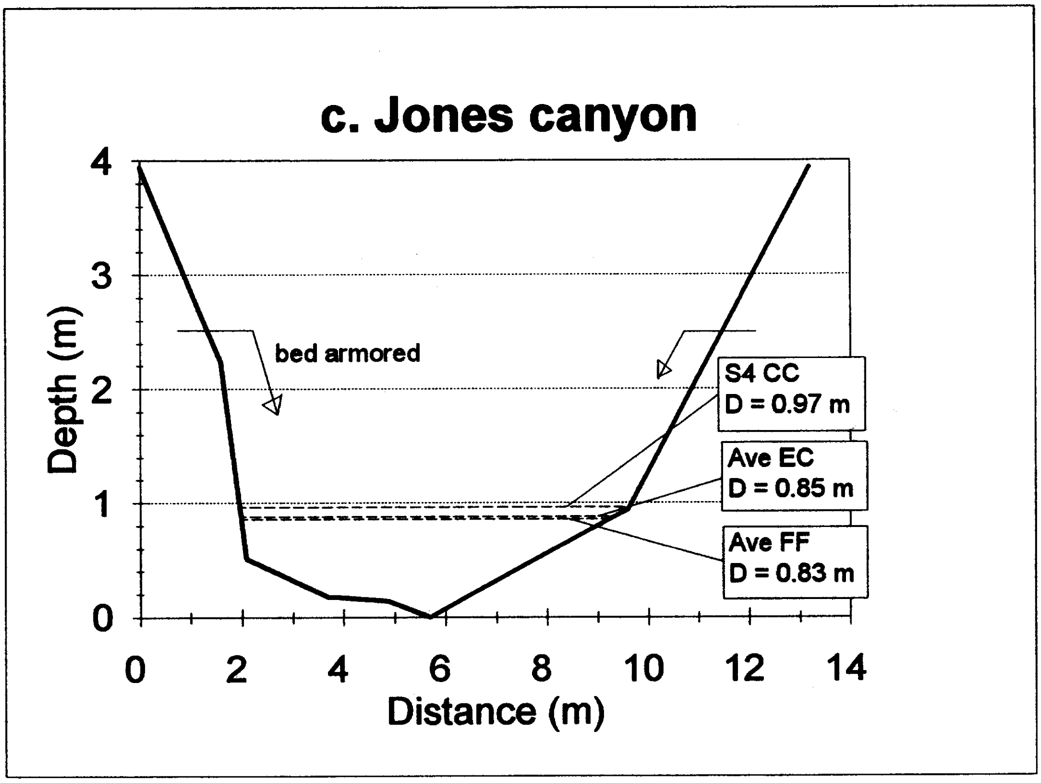
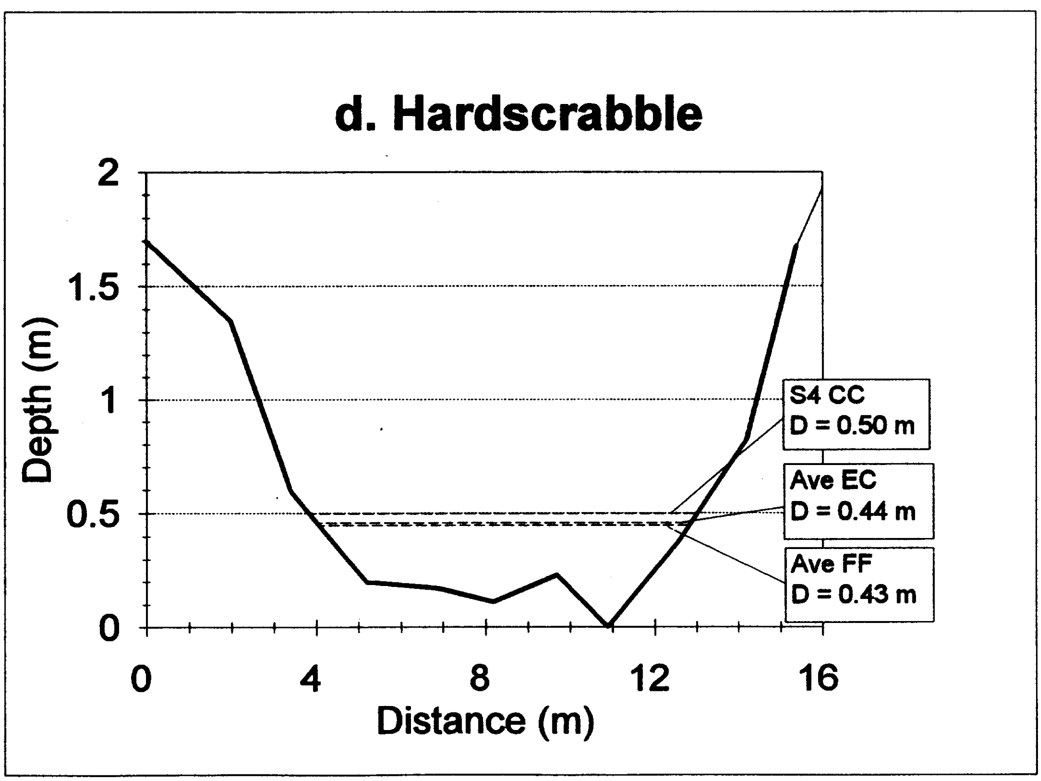
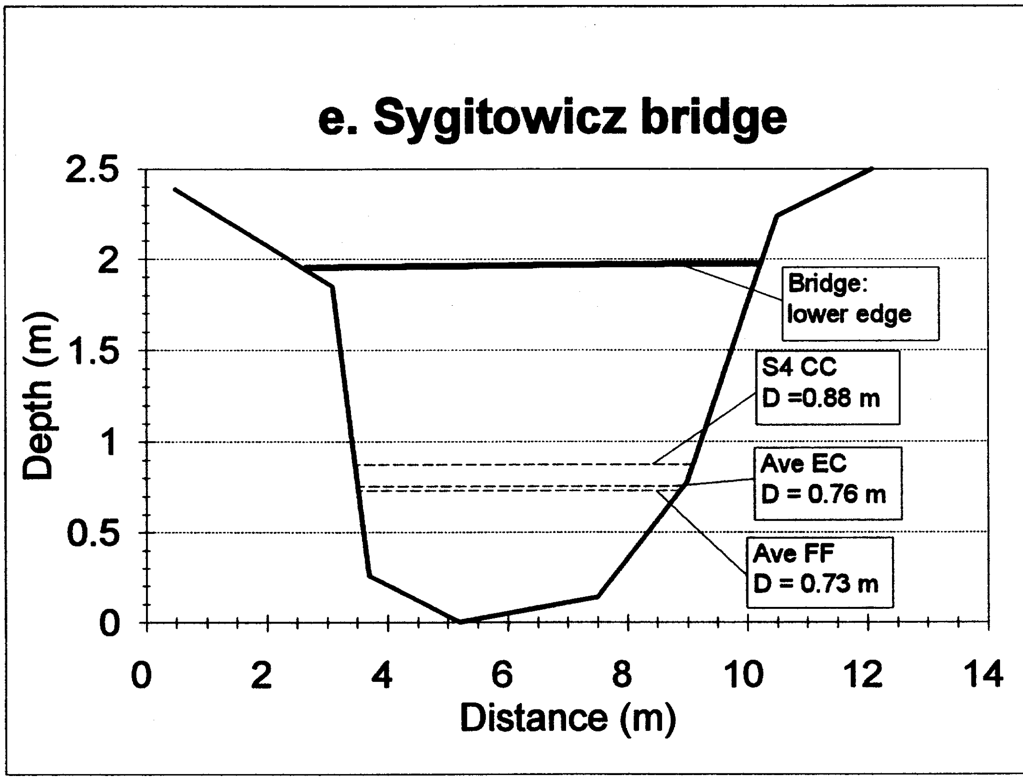


Figure 5-7 Diagrams of Cross-sections with flow levels predicted for three scenarios: Average storm - fully forested (Ave FF) and with existing cover (Ave EC), and Storm #4 completely clearcut (S4 CC).


c. Jones canyon
Depth (m)
Distance (m)
bed armored
S4 CC
D = 0.97 m
Ave EC
D = 0.85 m
Ave FF
D = 0.83 m


d. Hardscrabble
Depth (m)
Distance (m)
S4 CC
D = 0.50 m
Ave EC
D = 0.44 m
Ave FF
D = 0.43 m


e. Sygitowicz bridge
Depth (m)
2.5
2
1.5
1
0.5
0
0
2
4
6
8
10
12
14
Distance (m)
Bridge:
lower edge
S4 CC
D =0.88 m
Ave EC
D = 0.76 m
Ave FF
D = 0.73 m

m) above the pre-storm bed level (WCPD 1992). A simple comparison between aggradation and the predicted peakflow increases suggests that aggradation would be 60 times (1.2 m/.02 m) as effective at raising flow levels than peakflow enhancement. It can be argued that comparing the effects of peakflow enhancement and bed aggradation is artificial, since the two influences coincide and are additive during some large storms. However, the comparison merely supports the conclusion that massive inputs of sediment from mass wasting, rather than increased peakflows, are the primary cause of the overtopping of channels and bridges on alluvial fans that is often termed "flooding". This conclusion is similar to those from previous analyses of problems on other local alluvial fans (Warnick Watershed Analysis, Beschta et al. 1993).

5.5.2 Capacities of Culverts

Culverts installed for road crossing over small streams are often undersized to carry large peakflows (Piehl et al. 1988, Beschta et al. 1993). Where culverts are undersized, water may pond behind fills during large storms and the risk of plugging with debris is increased. Ponding or plugging can result in overtopping a road or fill collapse that may disable a road. Where such conditions occur, the potential for serious damage to downstream fish habitat, riparian systems, and/or other resources (e.g., roads, bridges, houses) is increased. The identification of undersized culverts allows landowners and managers to remove existing under-designed structures, or replace them with structures of increased capacity that will reduce the risk of failure.

In the Acme WAU, 19 stream crossing culverts (Figure 5-8) were investigated to determine their hydraulic capacity relative to large flows (Table 5-3). All culverts are located on Type 4 or 5 (i.e., non-fish bearing) streams that drain basins influenced primarily by forestry operations. Upstream drainage areas ranged from 20-290 ha (50-700 ac). Two culverts (at Falls and Hardscrabble Creeks) had been installed with concrete overflow structures and were not analyzed because of the reduced failure risk provided.

Hydraulic capacities for round culverts were determined using inlet-control nomographs for projecting inlets (AISI 1983). Capacity was determined for a headwater/diameter ratio of 1 because fills were generally not designed or constructed to withstand the added stress produced from ponding/saturation. Table 5-3 and the following discussion uses English units rather than metric in order to facilitate field application of results.

The hydraulic capacity of the investigated culverts was compared to estimated peakflows for two scenarios: (1) a 100-year peakflow and (2) a 50-year peakflow enhanced for rain-on-snow increases. Stream crossing culverts in the Sygitowicz and Jones Creek subwatersheds were increased by 26% to reflect modeling responses from harvesting for major drainages in the western portion of the WAU, while those of Tinling Creek subwatershed were increased by 11% to reflect results for the Eastern

Table 5-3 Capacity of stream crossing culverts in the Acme WAU

Site no.	Sub-watershed	Road	Culvert diam.[1] (in)	Culvert capacity[2] (cfs)	Drainage area (mi^2)	- Peakflow rate - 50-yr (cfs)	Enh[3] (cfs)	Capacity rating[4]	Risk to:[5]
0	Ws	Caron	42	47	0.24	63	78	I - 60	PR
1	Ws	S 26	24	11	0.08	31	39	I - 48	F,S
2	Ws	A-1000	48	65	0.22	58	72	M	---
3	Ws	A-1000	60	110	0.42	102	126	M	---
4	Ws	A-1000	36	32	0.19	51	64	I - 48	---
5	Ws	Turkington	48	65	0.17	60	74	M	PR
6	Ws	H-3000	60	110	0.20	54	67	A	---
7	Ws	Hwy 9	36+36	64	0.49	116	144	I - 72	PR
8	Ws	Hwy 9	30	20	0.25	83	103	I - 60	PR
9	Es	Mosqto Lk	36	32	0.21	31	35	M	PR
10	Es	N-1007	36	32	0.20	30	34	M	---
11	Es	N-1000	36	32	0.18	27	31	A	---
12	Es	Strand	36+30	52	0.77	96	108	I - 60	PR
13	Es	S 28	60	110	0.77	96	108	A	---
14	Es	N-1200	60	110	0.39	53	60	A	---
15	Es	N-1000	30	20	0.29	41	47	I - 48	---
16	Es	Strand	4x6'box	~140	1.11	131	148	M	PR
17	Es	N-1500	48	65	0.56	73	82	I - 60	---
18	Es	N-1000	24	11	0.27	39	44	I - 48	---

1 - Culvert diameter in inches; a "+" indicates two culverts.
2 - Capacity methodology documented in Section 4.1.2
3 - 50-year flow enhanced to account for maximum rain-on-snow (+20% for western subwatershed, +11% for eastern)
4 - Capacity ratings: I = inadequate to pass 50-year flow, number indicates diameter needed. M = marginal: adequate to pass unenhanced 50-year flow only. Next larger culvert size would be adequate. A = adequate to pass enhanced 50-year flow.
5 - Culvert failure could result in mass failure risk to: fish habitat (F) or public roads (PR). Damage to logging roads and fine sediment transport to fish habitat is assumed likely from any site.

SubWAU. These increases reflect flow rates projected if the entire drainage above a crossing was logged or burned, thus representing a "worst-case" situation. Because enhanced 50-year peakflows equaled or exceeded the 100-year unenhanced peakflows, the enhanced 50-year peakflow was used to establish the capacity rating for stream crossing culverts (Table 5-2).

The 50-year and 100-year peakflows were estimated using regional USGS equations based on drainage area, annual precipitation, and flood region (Cummans et al. 1975). Because the "flood region" boundary runs through the WAU, the runoff per unit area for a given storm recurrence interval is approximately twice as high for basins west of the South Fork than for those east of the South Fork. Topographic differences provide several physical explanations for greater peakflows from Stewart Mountain (i.e., west-side) basins: greater orographic influence and exposure to southwesterly storm track, and greater rain-on-snow influence because of elevation differences.

Most of the culverts analyzed (15 of 19) were not large enough to pass the design peakflow (Figure 5-8, Table 5-3). For six of the 15 undersized culverts, existing capacity is considered "marginal" because the current capacity is adequate without any rain-on-snow enhancement. Until 1994 when hydraulic standards were upgraded to require 100-year recurrence interval design, the six "marginal" sites would have met the previous 50-year design criterion. The other nine culverts appear to be substantially undersized, including three that are inadequate for even a 2-year peakflow (i.e., 1, 8, and 18; Table 5-3). No obvious correlations were noted between culvert adequacy and basin size or location within the WAU. However, culverts on logging roads are more likely to be adequately sized (four of 12 rated adequate) than culverts on "public" roads. Among culverts on County Roads and Highway 9, none of the six appear to be adequate.

Since installation, some of the apparently undersized culverts have likely withstood peakflows that exceeded their calculated capacities as indicated in this analysis. Greater flow rates can be accommodated when backwater ponding produces an increased flow velocity through the culvert, diverts water into a ditchline, or overflows the road. Evidence of past ponding and overflow were observed at several sites during the field investigation.

Fine sediment transported from an undersized or damaged culvert could produce damage to downstream fish habitat, though moderate topography at most of the inventoried sites suggests that dam-break flood or debris flow initiation is unlikely. The single exception is Site 1 in the headwaters of Hardscrabble Creek which could initiate a debris flow. A debris flow runout model (Benda and Cundy 1990) suggests that the terminal deposit could damage downstream fish habitat and possibly Hillslope Road, but is expected to stop above buildings located on the lower fan.

5.6 CONFIDENCE IN ANALYSES

A rain-on-snow modeling approach was undertaken, as a Level 2 Analysis, to specifically evaluate potential changes in peakflows associated with the conversion of mature forest vegetation to younger age classes as a result of logging activities. Input data describing watershed elevations (from USGS topographic maps) and forest cover conditions (from assessment of aerial photographs and local ground-truthing) are considered to provide a reasonable perspective of general conditions. The quality of precipitation, temperature, and windspeed data is more variable and problematic. Such measurements are likely of excellent quality at the point of measurement and provide important information regarding the temporal distribution of these variables during actual storms. The rainfall data used in these analyses was obtained from within 15 km of the WAU and are expected to provide a good representation of temporal rainfall amounts during large storms. Because frontal air masses tend to have regional characteristics, the use of SEATAC data may also provide a reasonable level of information regarding time series of air temperature and windspeed data. However, the need to extrapolate time series of rainfall, temperature, and windspeed to the Acme WAU from stations outside the WAU boundaries obviously introduces the potential for various types of errors. Although the ability to exactly represent onsite conditions within the Acme WAU for a specific storm are only fair-to-good, the data likely provide a good-to-excellent representation of conditions that occur during typical large storm events.

A general snowpack water equivalent versus elevation relationship, established from regional data, provided the basis for estimating elevation zone water equivalents at the start of each storm. Although January 1 snowpack water equivalents are closely associated with elevation, the applicability of this general relationship to the specific storms that occur at various times is problematic. Similarly, available snowmelt lysimeter data collected for openings and forest conditions in the north Cascades were used as a basis for estimating differences in snow accumulation patterns that might occur between forested and clearcut areas. Even though this research data may be locally accurate for the north Cascades and represent perhaps the best data available, the magnitude of difference in melt rates and volumes for openings and forested conditions and their applicability to forest openings in the Acme WAU is only considered fair.

The confidence in the widely accepted snowmelt equations (US Army Corps of Engineers 1956) is generally considered as good. However, these equations, which were originally developed nearly 40 years ago in the central Oregon Cascades, have not been rigorously tested against small watershed data for much of the Pacific Northwest. Similarly, the Antecedent Precipitation Model, also developed from watershed data in Oregon, has not been rigorously tested over a wide range of watersheds in the Pacific Northwest. Never-the-less, in combination these snowmelt equations and modeling efforts provide the capability of estimating basin-specific changes in peakflow hydrology associated with changes in forest cover. The combined confidence in these two simulation components is considered fair to good.

In spite of limitations imposed by the quality of estimated meteorological conditions and snowpack water equivalents, or the inadequacies of the snowmelt equations and runoff model, whenever possible this analysis attempted to utilize local data or research results to help assist in characterizing the "site-specific" conditions associated with the Acme WAU. Exact replication of a specific storm and its hydrograph was not the intended purpose or expected outcome of these simulations. Instead, the replication of "representative" large storms associated with rain-on-snow conditions was undertaken so that relative differences in peakflows due to forest harvesting could be evaluated. The use of measured peakflow data for frequency analysis provides another example of the attempt to localize these results as much as possible to the Acme WAU. Thus, the overall confidence in the estimated changes in rain-on-snow peakflows associated with harvesting practices is considered to be good.

With regard to the assessment of stream crossing culverts, the confidence in flow capacities is good and the estimates of site-specific peakflows from regional equations are fair. However, because of the relatively large under-design for many of the culverts, the confidence in the general conclusions regarding undersizing is good.

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APPENDIX 5-1

RAIN-ON-SNOW HYDROLOGIC ANALYSIS: ACME WATERSHED ADMINISTRATIVE UNIT

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RAIN-ON-SNOW HYDROLOGIC ANALYSIS:
ACME WATERSHED ADMINISTRATIVE UNIT

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RAIN-ON-SNOW HYDROLOGIC ANALYSIS:
ACME WATERSHED ADMINISTRATIVE UNIT

INTRODUCTION

For the Cascade Mountains of northwestern Washington, large rainfall events are a common occurrence. During the late fall, winter, and early spring periods, moist air masses originating from the Pacific Ocean move inland and release substantial amounts of moisture over periods of several days or longer. These large storms are responsible for generating large volumes of runoff and high peakflows. A wide variety of factors affect how this moisture and any additional snowmelt is converted to streamflow. For example, variations in local weather patterns (including precipitation amount, air temperature, and windspeed), in conjunction with snowpack conditions, topography, geology, soils, vegetation and landuse practices associated with specific watersheds can all have a role.

Forest soils in the Pacific Northwest are noted for their naturally high infiltration capacities. Thus, moisture from rainfall and snowmelt typically infiltrates these soils with overland flow being uncommon. Because of low precipitation amounts in summer and high evapotranspiration demand by forest vegetation, soil moisture levels during the early autumn months are generally low. Thus, much of the rainfall from early fall storms is utilized to recharge depleted soil moisture storage and streams have a diminished response to rainfall events during this time of the year. However, after a series of rainfall events soils tend to become recharged (i.e., approach field capacity) and any ensuing rainfall or snowmelt moves rapidly towards topographic depressions and stream channels via subsurface flow.

For steep headwater portions of a watershed, exceptionally large rainfall events can be associated with the occurrence of landslides and mass soil movements; low-lying areas and floodplains may be prone to overbank flows. Not only do these high-flow events normally transport considerable amounts of sediment but they also represent an important factor affecting the characteristics and development of alluvial channels and riparian plant communities.

From late fall to early spring, recurrent high streamflows are a normal pattern in northwestern Washington during the passage of extensive frontal storms through the region. Precipitation from these storms is orographically enhanced as moist air masses are forced upward and over the Cascades. Hence, the higher elevations of a watershed typically receive more precipitation than lower elevation areas within the drainage.

The hydrology of low-elevation areas west of the Cascades crest is often characterized as being "rain dominated". Snowpack accumulation is typically infrequent and rainfall is the prevailing form of precipitation. However, with increasing elevation and a corresponding decrease in air temperature, the predominant form of precipitation during a winter storm often shifts to snow. Along the crest of the Cascades, the form of precipitation is commonly snow and seasonally permanent snowpacks develop each winter.

Intermediate between the higher elevations of the Cascades and the lower elevations of the valley floors is found the "transient snow zone" where winter precipitation, depending upon storm characteristics, can occur as either rain or snow. Within the transient snow zone, it is not uncommon for shallow snowpacks to develop several times each winter. When snowpack accumulation is followed by a frontal storm with relatively warm air temperatures and large rainfall amounts, snowpacks within the transient snow zone are prone to rapid melt. Rain-on-snow conditions are considered to be the primary cause of high flows from mountainous watersheds of throughout much of the western Washington Cascades. In western Washington, the transient snow zone is generally considered to occur between elevations of approximately 500 and 1,200 m (1,600-4,000 ft) (Department of Natural Resources 1991).

Perhaps the major hydrologic significance of the transient snow zone is that the melting of moisture from mountain snowpacks augments rainfall amounts that occur during a rainstorm. Depending upon the initial snowpack characteristics, particularly snowpack water equivalent, and meteorological conditions during a storm (e.g., air temperature and windspeed), the amount of additional meltwater released from these snowpacks can be significant. Furthermore, the presence or absence of forest canopies can influence both snowpack accumulation patterns and rates of snowmelt during a storm. Hence, the purpose of this analysis was to evaluate potential changes in rain-on-snow peakflows that might result from forest harvesting in the Acme Watershed Administrative Unit (WAU). While forest harvesting of mountain watersheds in the Pacific Northwest is generally followed by significant increases in annual water yields, the effects of forest harvesting on peakflow magnitudes are less certain.

RAIN-ON-SNOW PROCESSES

Air temperatures associated with major frontal storms that pass through the mountainous areas of the north Cascades each winter have a particularly important influence on the resultant flow regimes for a given watershed. For example, relatively cold air temperatures during a storm will cause snowfall to occur over a wide range of elevations. In contrast, relatively warm air temperatures will cause most precipitation to occur as rain. When air temperatures approach the freezing point, precipitation may occur as either rain or snow. Because of the general trend toward colder air temperatures at increasing elevations, it is also common during a particular storm for rainfall to occur at the lower portions of a large watershed while the upper portions are experiencing snowfall. Furthermore, the demarcation between rain and snow can shift up or down the watershed as a storm progresses and as regional air temperatures change. Such elevational shifts in air temperatures have a profound effect on storm hydrographs because of their influence on both the form of precipitation (i.e., rain versus snow) and snowmelt processes.

Large amounts of naturally occurring rainfall are necessary to generate high streamflows from mountainous watersheds in the western Cascades. These flows can be further increased if (1) substantial amounts of snow have previously accumulated on the watershed and (2) air temperatures are relatively warm during the rainfall period. The convective transfer of sensible heat (warm air) and latent heat (heat released during condensation) from a relatively warm and humid air mass to the snowpack, in addition to heat contained in the rain, are responsible for causing rapid snowmelt. Rainfall amounts are thus enhanced by this additional meltwater and the total amount of water delivered to forest soils is increased. Thus, the amount and timing of this "additional" water may have a significant effect on peakflows occurring at the mouth of a watershed. When such a situation occurs, it represents a classical "rain-on-snow" event.

The creation of forest openings from fire, blowdown, or forest harvesting may also influence runoff amounts and timing during rain-on-snow events. The removal of forest canopies is important largely because of (1) its influence on snowmelt accumulation patterns and (2) the rate at which heat is transferred from the air to the snowpack during periods of rainfall.

With regard to snow accumulation, a large number of studies from "snow-dominated" systems, mostly in the Rocky Mountain region or high elevation areas of the California Sierra Nevada and Oregon Cascades, indicate a greater snowpack water equivalent is generally found in forest openings than in the surrounding forest (Anderson et al. 1976, Brooks et al. 1991). Increased snowpack water equivalents of 5 to 40% are likely when the diameter of a forest opening or clearcut is less than 10H (where H represents the height of the surrounding forest) (Troendle 1983). For trees averaging 45 meters in height, a 10H circular opening would encompass approximately 16 ha. For forest openings larger than 10H, snowpack accumulation in the Rocky Mountain region is projected to be less than that of the adjacent forest (Troendle 1983).

Whenever natural forest openings or clearcuts in the transient snow zone alter snowpack accumulation patterns, the amount of snowpack water equivalent that is locally available at the onset of a rain-on-snow event should also be affected. Unfortunately, snow accumulation patterns associated with clearcuts of various sizes in the transient snow zone of the Pacific Northwest have been little studied and only limited information is available in the scientific literature. Recent studies (e.g., Coffin 1991) provide some information regarding the interception and storage of snowfall under forest canopies and in clearcuts.

Because the presence or absence of forest vegetation in the transient snow zone affects the dynamics of snow interception and accumulation, outflow at the bottom of a snowpack under a forest canopy and in an opening will likely reflect these differences. Connelly and Cundy (1992), originally reported by Coffin (1991), summarize "forest" and "opening" outflows for 11 rain-on-snow events. Results for the 11 events indicate that snowpack outflow from an opening ranged from 21 to 138% greater than the outflow measured for a forest snowpack. On average, an additional 28 mm (1.1 inches) of moisture was available from snowpacks in openings in comparison to those under a forest canopy; for approximately 80% of the reported events the additional moisture was $\leq$38 mm (1.5 inches). For the snowmelt simulations summarized in this report, snowpack water equivalents for forest openings (clearcuts) were increased an additional 38 mm in comparison to adjacent forest snowpack water equivalents at the beginning of each simulation.

Although the heat content of warm rain can provide some energy for melting a snowpack, most energy in forest openings usually becomes available to the snowpack as a result of relatively warm moist air moving across the snowpack (Corps of Engineers 1956). In such instances, convective processes associated with air moving across forest openings accentuate the transfer of both sensible and latent heat to the snowpack. Sensible heat represents the transfer of energy from relatively warm air (greater than 0°C) to a cold snowpack (at or below 0°C); latent heat transfer occurs with the release of energy when water vapor in the air condenses on the snowpack surface. Because of the differing wind patterns and velocities under a forest canopy and in openings, the transfer of sensible and latent heat is generally more efficient in forest openings. Hence, snowpacks in forest openings are likely to melt faster during rain-on-snow conditions than snowpacks under a forest canopy.

Harr (1979) used relationships developed by the Corps of Engineers (1956) to analyze how various energy transfer components influence snowmelt for several sets of meteorological conditions. His analysis indicated that sensible and latent heat transfers provided the greatest proportion of energy to a snowpack during rain-on-snow conditions. The relative importance of heat from rainfall increased with storm size and became the dominant energy source for snowmelt when precipitation amounts generally exceeded 180 mm (7 inches).

The amount of water flowing from the bottom of a snowpack during a rain-on-snow event is of fundamental importance regarding the generation of peak streamflow from mountain watersheds. Differences in snow accumulation and melt processes that occur between forested and non-forested areas may thus have an important effect on the magnitude of instream flows that are generated during these events. A principal goal of this analysis is to evaluate the relative effect that forest harvesting may have upon peakflows during rain-on-snow conditions. Because rainfall and snowmelt water generally moves towards streams as subsurface flow, this analysis assumes that changes in peakflows, if any, are primarily driven by the relative availability of water to hillslope soils. Increased availability of moisture at the soil surface may also increase pore water pressures of subsoils and potentially decrease the stability of slopes prone to shallow mass failures (Ziemer and Albright 1987).

The analysis reported herein focuses on peakflows during relatively large storm events. Although large percentage differences in peakflows can occur between forested and clearcut watersheds in the Pacific Northwest during the early autumn storms when soil moisture differences are usually most pronounced, such events are of much smaller magnitude than those simulated in this analysis. These smaller events are also of relatively little significance with regard to the occurrence of landslides, dambreak floods, and periods of significant bedload sediment transport.

Several additional features of this analysis need to be noted. Interception losses of forest vegetation were not included in the preceding simulations. The amount of interception storage afforded by forest vegetation is generally small (usually 3 mm or less) and is satisfied early during a storm event. Similarly, interception losses due to evaporation would be expected to remain low during major rainfall events when humidities are high. Thus, relative differences in interception loss between forest and clearcut comparisons from the combined effects of interception storage and evaporative losses should have little effect on peakflows during large storms for forested and clearcut conditions.

METHODOLOGY

Rain-on-snow dynamics for the Acme WAU were simulated for forested and harvested areas to determine the potential effects of harvesting upon storm hydrographs. These simulations were accomplished by utilizing actual time series of precipitation amounts and associated meteorological characteristics (air temperatures and windspeeds) for large winter storms, topographic information from the Acme WAU, and information on the history of forest harvesting within the WAU. This information was used in conjunction with snowmelt equations and a rainfall-runoff model.

Design-storm concepts have been widely applied for a variety of hydrologic considerations in urban and agricultural areas, often in conjunction with the Soil Conservation Service (SCS) Runoff Curve Number Model or unit hydrograph models. However, an evaluation of the SCS Runoff Curve Number Model by Fedora (1987) indicated that it is not an appropriate methodology for simulating peakflows from large winter storms associated with forested watersheds of the Pacific Northwest. The highly variable temporal distribution of rainfall intensities and amounts during most winter storms make the SCS Runoff Curve Number Model particularly inappropriate. Furthermore, whereas the SCS Runoff Curve Number Model has been developed for watersheds where overland flow is a significant component of storm runoff, such conditions are not common for forested watersheds in the Pacific Northwest.

The design-storm approach also has several serious limitations (Bedient and Huber 1988), particularly when applied to conditions found in the Pacific Northwest. For example, the intensity-duration-frequency relationships for a given location do not represent time histories of real storms. Instead, intensities represent mathematically smoothed representations from several types of storms. Antecedent conditions are seldom known and must be estimated. Furthermore, the duration of a design storm is not the duration of an actual storm. The highly varied time histories of actual precipitation intensities for large storms in the Pacific Northwest would indicate that the utilization of a design storm approach is inappropriate. Incorporating "design storm" methodologies for simulating snowmelt processes during rainfall events is similarly untenable.

Because precipitation amounts and air temperatures tend to be correlated with elevation, the distribution of land area by elevation zones represents an important feature of mountain watersheds where rain-on-snow events are common. An area-elevation relationship for the Acme WAU (Figure 1) indicates that nearly 30% of the entire WAU lies within the 500- to 1,200-m transient snow zone. Approximately 40% of the WAU occurs below 120 m in elevation and represents the valley floor associated with the South Fork Nooksack River.

In an attempt to more accurately simulate changes in stormflow hydrology that occur with differing elevations and areas within the Acme WAU, it was subdivided into eastern and western components (Table 1; Figure 2). The Eastern and Western SubWAUs are comprised of all lands above 120 meters of elevation on the east and west side of the valley. These lands consist predominantly of commercial forest land. In addition, because it has a relatively high proportion of its area in the transient snow zone, peakflow simulations were undertaken for the Jones Creek Watershed (for that portion above 120 m) which lies in the southwestern portion of the WAU. Because the valley portion of the Acme WAU (that land below 120 m in elevation and located between the Eastern and Western SubWAUs) is well below the general lower range of the rain-on-snow zone, contains mostly flat or gently sloping terrain, and is largely used for agricultural purposes, peakflow simulations were not undertaken.

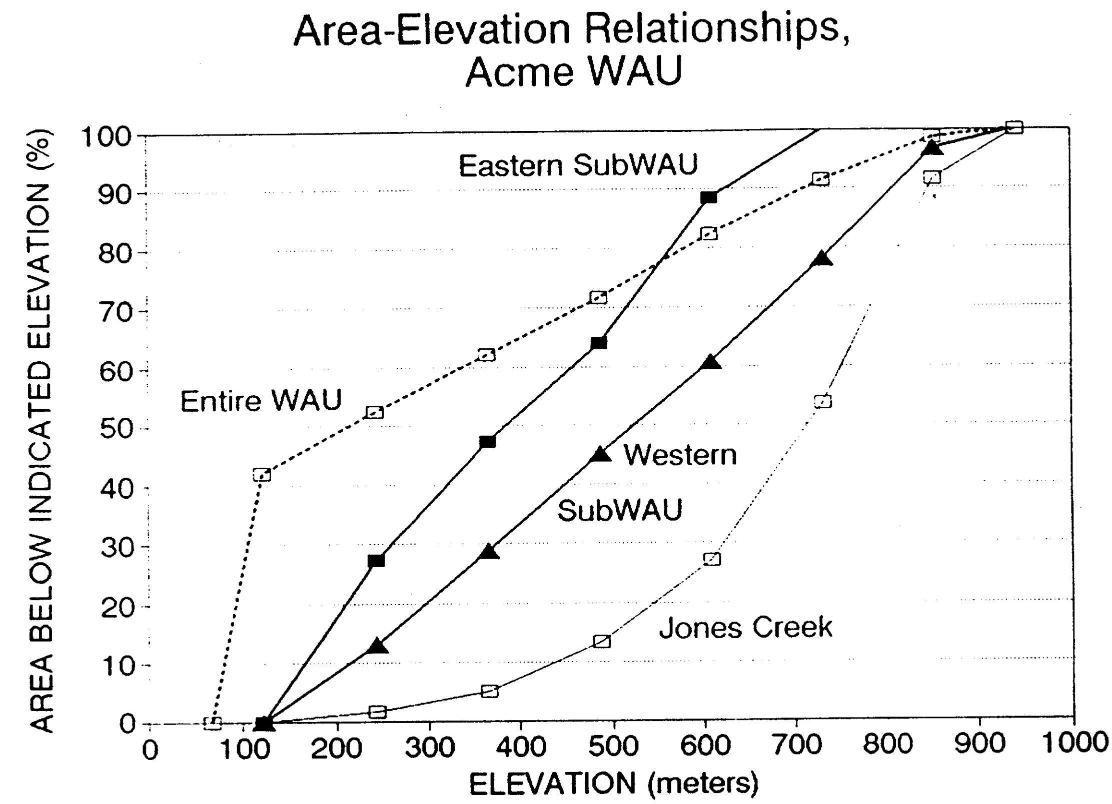


Figure 1 **Area-elevation relationship for the Eastern SubWAU, Western SubWAU, Jones Creek Watershed, and the Acme WAU.**

Table 1 Area-elevation characteristics of the Acme WAU.

Subwatershed	Area (% of WAU)	Median Elevation (m)	Elevation Range (m)
Acme WAU	100	220	70-840
Eastern SubWAU	23	390	120-605
Western SubWAU	39	530	120-790
Jones Creek Watershed	9	710	120-840

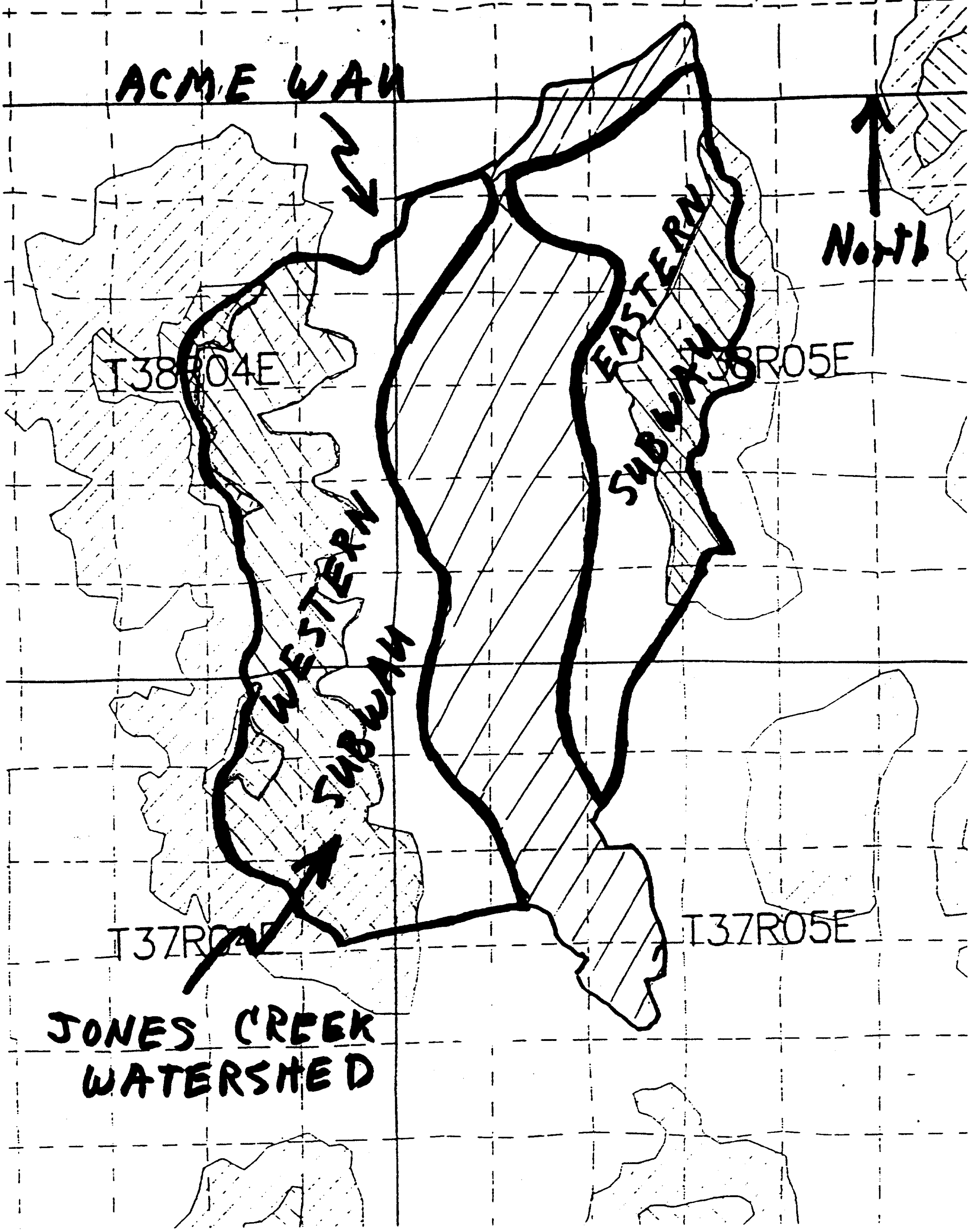


Figure 2 Generalized location map of the Eastern SubWAU, Western SubWAU, and Jones Creek Watershed.

Rainfall/Snowmelt Simulations

For simulation purposes, an elevation band approach was utilized for the Eastern SubWAU, Western SubWAU, and Jones Creek Watershed simulations whereby each of these areas was subdivided into four elevation zones of equal area (Table 2). Storm precipitation and snowmelt dynamics within each zone were simulated separately for each area. These three areas were selected for detailed analysis because they represented predominantly forested areas above the valley floor and have experienced significant amounts of timber harvesting in the past.

The National Weather Service Station at the Nooksack Hatchery, located approximately 15 km north of the center of the Acme WAU, was chosen to index storm precipitation amounts and timing for rain-on-snow events. Although the elevation of this station is relatively low (i.e., 125 m) in comparison to much of the Acme WAU, the station's relative closeness to the WAU was considered an important asset for obtaining representative time series of precipitation data for large storms. Furthermore, its precipitation records reflect much of the regional orographic enhancement that occurs during winter frontal storms.

Precipitation records from the Nooksack Hatchery Station for a 15-year period (i.e., 1976-90) were used for this analysis, however several years had only partial records. From inspection of daily and hourly amounts, the five largest precipitation events occurring within the 15-year period of record were selected for use in rainfall-snowmelt simulations. These five storms were used to provide a basis for assessing the relative importance of forest harvesting on snowmelt and runoff dynamics associated with the Acme WAU. Published hourly precipitation amounts from the Nooksack Weather Station were used for developing bihourly precipitation estimates for each of the four elevation zones within each of the three subwatersheds. Measured precipitation amounts at the Nooksack Hatchery were increased with elevation to provide more representative estimates of precipitation amounts at the higher elevations of the watershed.

In addition to areal estimates of precipitation amounts that were required for subwatershed simulations, companion estimates of air temperature and windspeed were also needed for use in snowmelt equations. Air temperature and windspeed values from published trihourly values for the National Weather Service Station at the SEATAC Airport were extrapolated to the Acme WAU. For example, a moist adiabatic lapse rate of 6° C per 1,000 m (Linsley et al. 1982, Washington Forest Practices Board 1992) was used for extrapolation of air temperature data to each elevation zone on the Acme WAU.

Rainfall/Runoff Model

For Pacific Northwest watersheds, where major storms tend to be of relatively long duration (i.e., several days or more), the effectiveness of rainfall in generating a storm

Table 2 Elevation band characteristics for the Eastern SubWAU, Western SubWAU and Jones Creek Watershed (Note: elevation bands comprise 25% of the area within a give subWAU or watershed), Acme Watershed Administrative Unit.

Elevation Bands	Median Elevation m (ft)	Elevation Range m (ft)
EASTERN SUBWAU; Area = 19.0 km² (7.32 mi²)		
A	605 (1985 ft)	540-670 (1722-2198 ft)
B	475 (1585 ft)	385-540 (1263-1772 ft)
C	310 (1017 ft)	230-385 (755-1263 ft)
D	175 (574 ft)	120-230 (394-755 ft)
WESTERN SUBWAU; Area = 39.3 km² (15.16 mi²)		
A	790 (2592 ft)	710-925 (2329-3035 ft)
B	620 (2034 ft)	525-710 (1722-2329 ft)
C	430 (1411 ft)	335-525 (1099-1722 ft)
D	240 (787 ft)	120-335 (394-1099 ft)
JONES CREEK WATERSHED; Area = 6.1 km² (2.37 mi²)		
A	840 (2756 ft)	800-942 (2625-3091 ft)
B	760 (2493 ft)	725-800 (2379-2625 ft)
C	660 (2165 ft)	580-725 (1903-2379 ft)
D	470 (1542 ft)	120-580 (394-1903 ft)

hydrograph depends on both (1) the total amount of rainfall and (2) the time distribution of that rainfall. Although high rainfall intensities during a storm usually lead to high flows, watershed response to high rainfall intensities is further modified by antecedent precipitation amounts. With relatively long storm durations, the temporal distribution of rainfall amounts prior to a period of high intensity is a particularly important factor affecting peakflow. When snowmelt occurs during a rainfall event, this moisture is added to the amount of incoming rainfall. For areas within the Acme WAU, the combined moisture from rainfall and snowmelt provided an estimated of the total "rainfall" available for modeling purposes.

An Antecedent Precipitation Index (API) Model (Fedora 1987, Fedora and Beschta 1989) was utilized to simulate peakflows associated with rain-on-snow events. The model was originally developed for forested watersheds in the Oregon Coast Range to simulate peakflow hydrographs during winter rainfall events associated with varying storm intensities and durations. This model has also been used to simulate peakflows for tropical watersheds (Beschta 1990) indicating that it may have relatively widespread applicability. Ziemer and Albright (1987) used a similar API model for simulating the temporal dynamics of pore water pressure associated with subsurface flows in steep forested terrain; Kobashi and Suzuki (1987) utilized an API model in evaluating the critical rainfall required for generating slope failures and debris flows.

The API model essentially keeps track of preceding (antecedent) rainfall and snowmelt amounts during a storm to develop an "Antecedent Precipitation Index". The API model is mathematically formulated as:

$$API_t = (API_{t-1} * C) + P_t$$

where API_t = antecedent precipitation index at time t (mm)
API_{t-1} = antecedent precipitation index for the previous time interval t-1 (mm)
C = storm hydrograph recession constant for a watershed (dimensionless)
P_t = amount of rainfall and snowmelt that occurs from time t-1 to t (mm)

The temporal decay rate of antecedent precipitation is indexed by the storm hydrograph recession coefficient "C". This recession coefficient integrates various effects of soils, geology, topography, etc., upon runoff responses and can be determined by analysis of storm hydrographs from the watershed of interest. A lack of measured streamflow data for any of the Acme subwatersheds prevented using actual flow data for determining subwatershed recession coefficients. Instead, recession coefficients were estimated from a relationship provided by Fedora (1987).

Once C has been determined, streamflow can be estimated from the following equation:

$$Q_t = [I + (S)*API_t]^2$$

where I and S are regression coefficients representing the intercept and slope, respectively, of a line relating Q_t and API_t (Fedora 1987). Two-hour time steps were considered to be sufficiently short to provide reasonable simulations of storm hydrograph dynamics. Initial simulations indicated that simulated peakflows were relatively high in comparison to gaged peaks for watersheds near the Acme WAU (e.g., Lake Creek and Skookum Creek). Hence, the constant in the equation for calculating S was reduced from 13.6 to 13.0 to provide more reasonable approximations of actual peakflows. Although altering the coefficient reduced peakflow estimates, the relative comparisons between forest, clearcut, and existing conditions remained essentially unchanged.

The use of the API model for subwatershed flow simulations required elevation zone estimates of bihourly (1) rainfall amounts and (2) snowmelt. The combination of these moisture sources represented the total water available to the soil surface during a storm and allows the estimation of peakflow hydrographs at the mouth of the watershed. Rainfall or snowmelt that occurs within a couple of days prior to a peakflow event can significantly influence the magnitude of that peakflow. The necessity of considering both the timing and amount of antecedent precipitation for peakflow simulations provides the basis of the API model used in this analysis of the Acme WAU.

RESULTS AND DISCUSSION

Storm Characteristics

Total 4-day precipitation amounts for the five storm events ranges from 203 to 269 mm (8.0 to 10.6 in). Considerable variability is displayed in the temporal distribution of daily precipitation amounts measured at the Nooksack Weather Station (Figure 3). For example, Storms #3 and #5 have identical 4-day totals, but daily amounts vary dramatically. Similarly, Storm #2 has the greatest 4-day total precipitation of the five storms, yet the maximum daily amount for this storm is considerably less than that encountered for Storms #4 and #5. Differences in precipitation intensities are further demonstrated when cumulative amounts over time are tabulated (Figure 4). Maximum precipitation intensities of nearly 10 mm/hr (0.4 inches/hr) for extended periods (12 hours or more) occur within the precipitation time series of Storms #2, #4, and #5. The large variability in precipitation intensities and timing, as illustrated in Figure 4, indicate that the use of a spatially- and time-averaged design storm is not only unrealistic but also inadequate for assessing the hydrologic effects of rain-on-snow events.

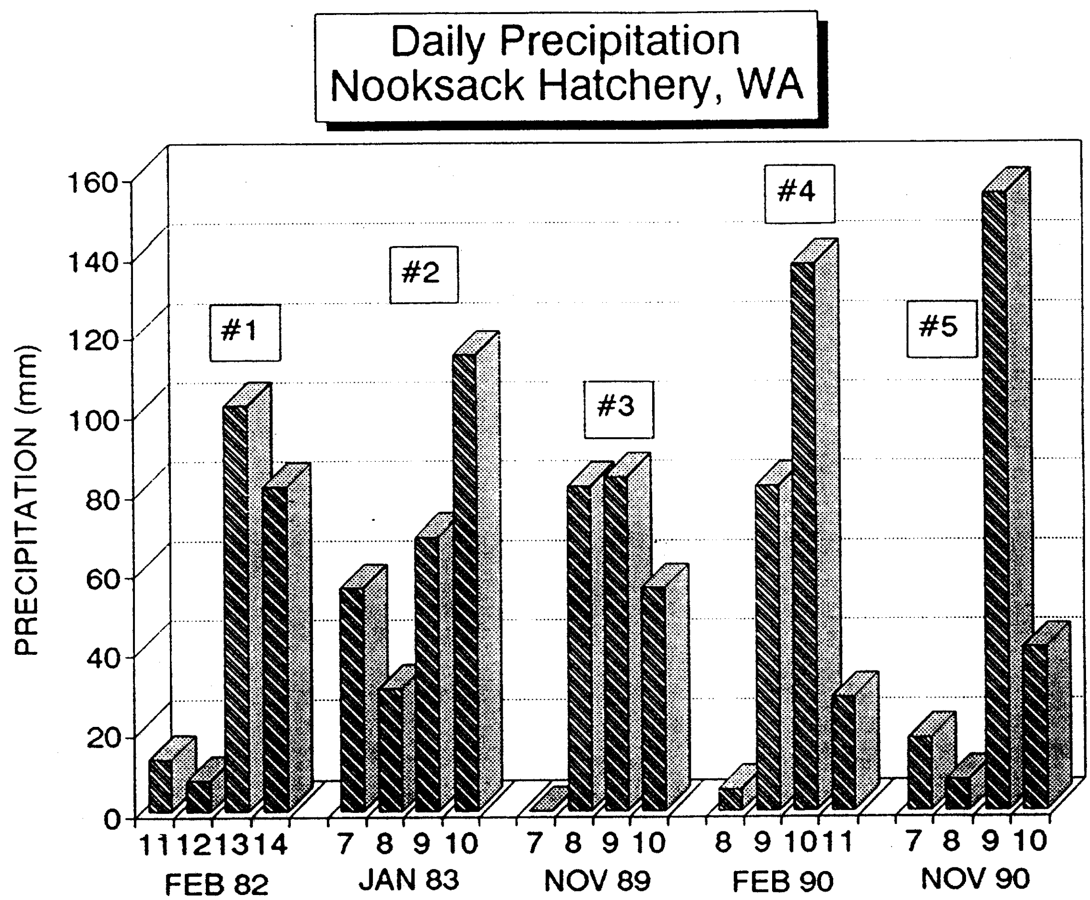


Figure 3 Daily precipitation amounts for Storms #1 through #5, Nooksack Weather Station.

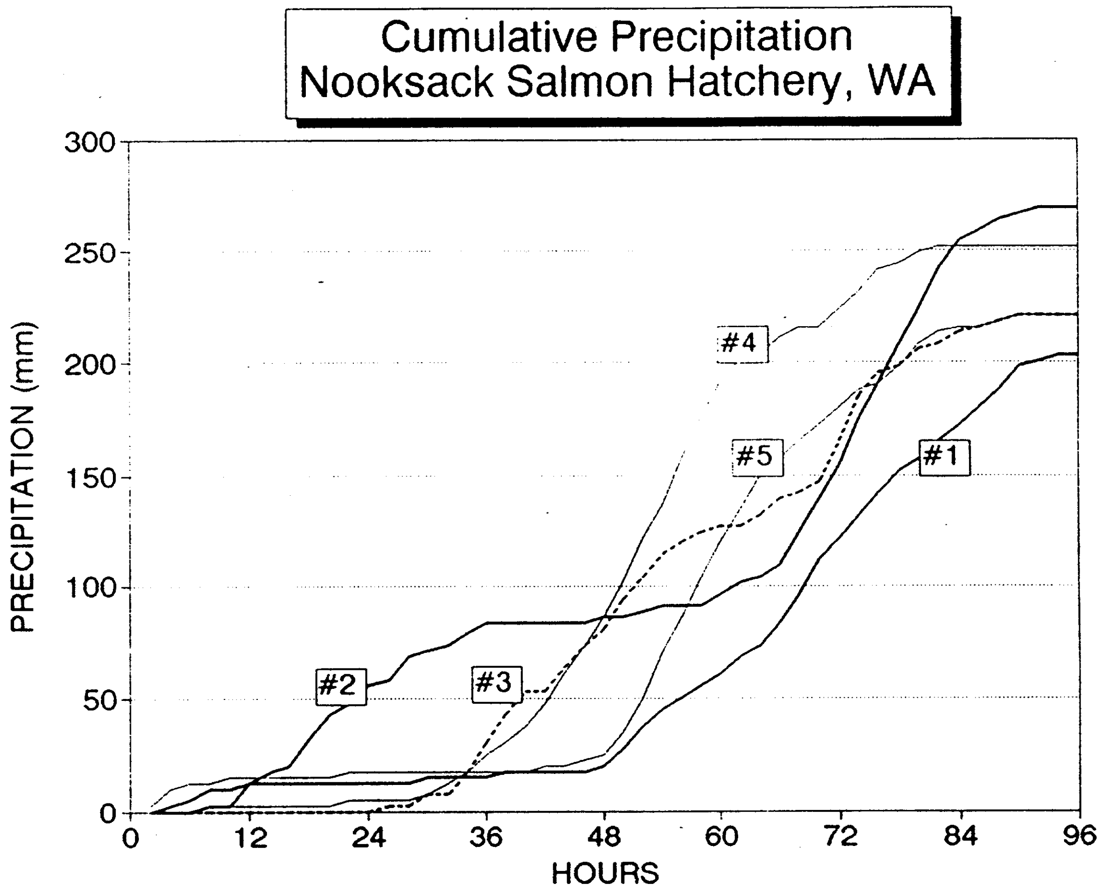


Figure 4 **Accumulated precipitation for Storms #1 through #5, Nooksack Weather Station.**

Temporal variability of precipitation intensities and their effects on streamflow are further compounded when companion time series of air temperature and windspeed, which affect snowmelt rates, are included. Data from the SEATAC Weather Station indicate that most of the storms began with relatively cool air temperatures. As a storm progressed, these temperatures generally increased during the 4-day period indicating the passage of a warm front, a condition characteristic of a typical "rain-on-snow" event (Figure 5). An exception to this general scenario occurred for storm #2 where the warmest air temperatures occurred relatively early followed by cooling and then warming during the 4-day period. Although daily windspeed patterns were highly variable at the SEATAC Weather Station (Figure 6), there was usually a trend toward increasing wind velocities during each storm with the exception again of Storm #4. In general, periods of high windspeed and high rainfall intensities occurred simultaneously.

Figures 4, 5, and 6 confirm that each storm represents a unique combination of precipitation and associated meteorological conditions. It is important that this "variability" in storm time series be retained and incorporated during modeling efforts that attempt to evaluate rainfall-snowmelt-runoff processes from forested watersheds.

Snowmelt Calculations

Quantitative estimates of snowmelt for the rain-on-snow simulations were based on snowmelt equations developed in the Pacific Northwest by the Corps of Engineers (1956). Separate equations are available for forested areas and forest openings; the equation representing forest openings was assumed to simulate clearcut conditions.

During each storm, snowmelt amounts were estimated on a bihourly basis for individual elevation zones within each of the three subwatersheds utilizing Corps of Engineers equations (Table 3) and extrapolated values of air temperature and windspeed from the SEATAC Weather Station. When the air temperature of a particular elevation zone was below freezing (0°C), it was assumed that all incoming precipitation was occurring as snow and that snowmelt was not occurring. At air temperatures above freezing, all precipitation was assumed to be rainfall and snowmelt calculations were performed. Air temperatures (at least within the upper elevation zones) were often below freezing during the early portions of a storm. At these elevations the onset of snowmelt was delayed until the occurrence of warmer air temperatures that typically occurred later during the storm.

During periods when air temperatures were greater than 0°C and snowmelt was occurring at a particular elevation band, windspeed information provided a basis for indexing the effectiveness of sensible and latent heat transfers to the snowpack. Without the effects of wind, snowmelt rates between forested areas and clearcuts would not be greatly different.

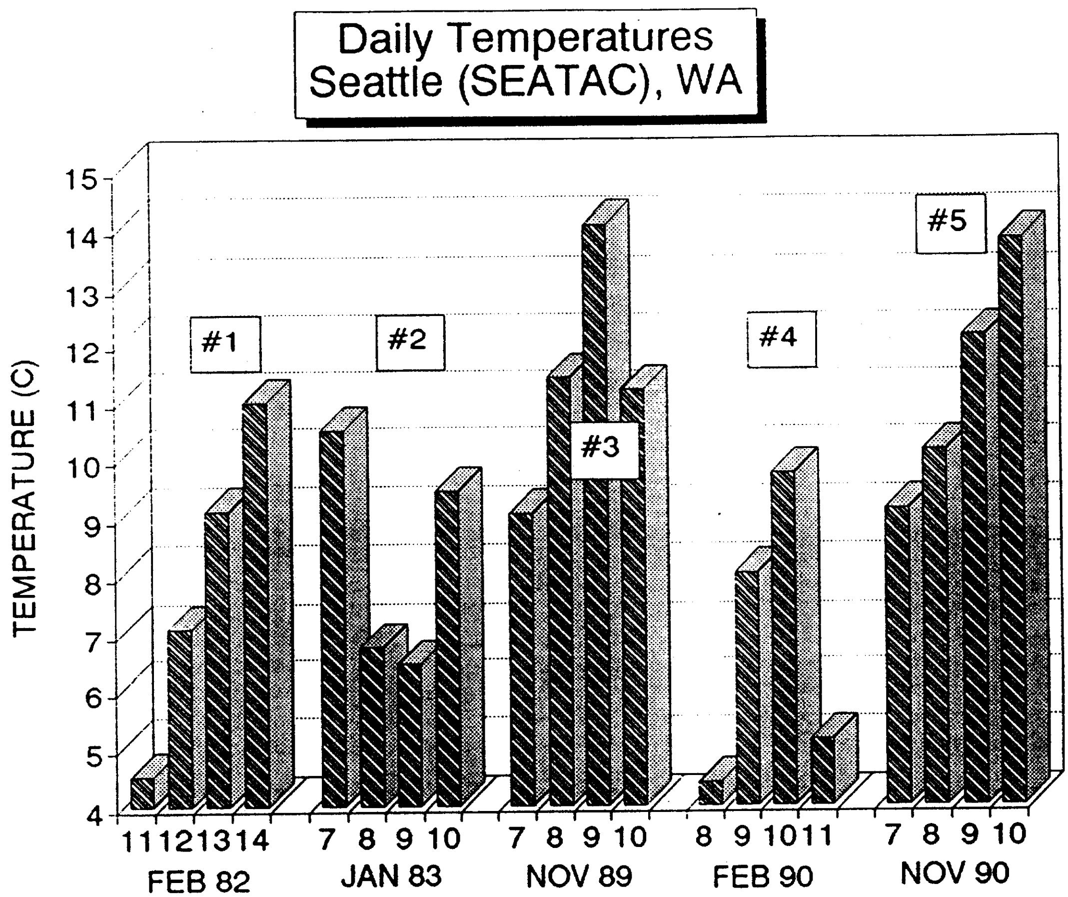


Figure 5 Average daily air temperatures for Storms #1 through #5, SEATAC Weather Station.

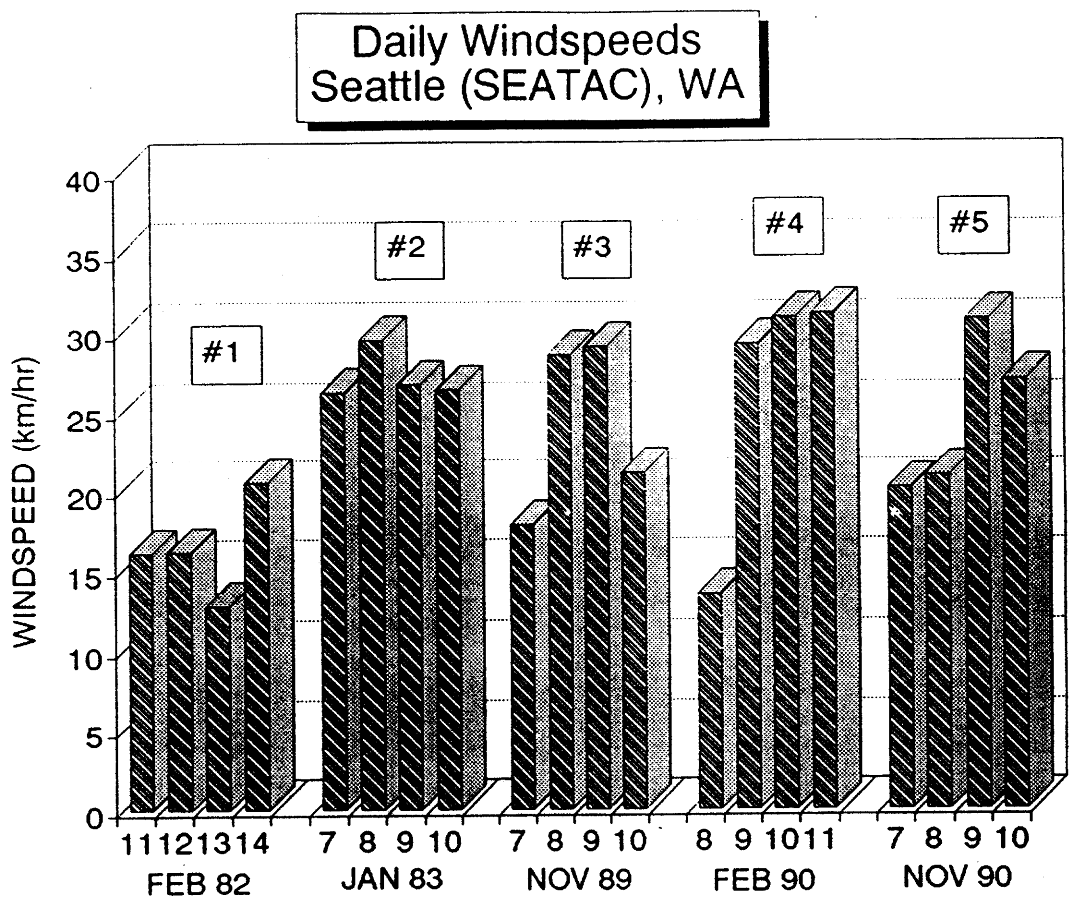


Figure 6 Daily windspeeds for Storms #1 through #5, SEATAC Weather Station.

Table 3 Summary of coefficients and equations used to simulate rain-on-snow melt rates, Acme Watershed Administrative Unit.

Precipitation, Temperature, and Wind Data

Precipitation data from the Nooksack Weather Station (elevation = 125 m) were used as the basis for estimating precipitation within each elevation zone of a subwatershed. Measured amounts at the Nooksack Hatchery Weather Station were increased with increasing elevation in an attempt to account for orographic enhancement. Corresponding air temperatures (adjusted by a moist adiabatic lapse rate of 6°C/1000 m) and windspeed data from the SEATAC Weather Station were also used to index storm conditions for subwatersheds within the Acme WAU.

Snowmelt Equations

The following equations were used to provide estimates of snowmelt during rain-on-snow events for clearcut and forested conditions (Corps of Engineers 1956):

Clearcut Conditions

$$M = [(0.029 + 0.0084\,k\,v + 0.007\,P_r)\,(T_a - 32)] + 0.09$$

where M = daily snowmelt for open or partly forested basin (inches)
k = basin constant related to exposure of basin to wind
v = mean wind speed (mph)
P_r = daily rainfall (inches)
T_a = mean daily temperature (degrees F)

Forested Conditions

$$M = (0.074 + 0.007\,P_r)\,(T_a - 32) + 0.05$$

where M = daily snowmelt plus rainfall for forested basins (inches)
P_r = daily rainfall (inches)
T_a = mean daily temperature (degrees F)

All analyses were undertaken using data in English Units; results were then converted to Metric equivalents for summarizing and presenting in the this report.

The delineation of precipitation amounts into either rainfall or snowfall, based on a single temperature criterion, represents an oversimplification of complex and interacting meteorological processes (Beschta 1975). Thus, the general lack of specific on-site observations of rain/snowfall information during rain-on-snow events in mountainous areas of the Pacific Northwest precludes a more sophisticated approach. Even so, the approach utilized in this analysis is expected to provide a reasonable approximation of snowmelt and streamflow dynamics during rain-on-snow conditions.

Rainfall/Runoff Simulations

For evaluating harvesting effects, three general types of rain-on-snow simulations were undertaken for the Eastern and Western SubWAUs and the Jones Creek Watershed. These types of simulations were chosen because they represented a range of existing and potential conditions found within the forested portions of the Acme WAU. The rainfall/snowmelt simulations involved the following watershed conditions:

Fully Forested: The entire subWAU or watershed was assumed to be covered with forest stands $\geq$25 years old.

Existing Conditions: Existing information on forest age classes was used to apportion peakflows associated with forested and clearcut conditions.

Entirely Clearcut: The entire subWAU or watershed was assumed to have been recently clearcut (i.e., age classes of $\leq$10 years old).

The "Fully Forested" simulations provided a baseline estimate of streamflow responses to large storms for subdrainages of the Acme WAU assuming these areas were entirely forested with mid- to late-successional age classes. The "Existing Conditions" simulations were undertaken to provide estimated increases in peakflows associated with existing distribution of forest age classes within a subWAU or watershed. To account for expected peakflow changes associated with the Existing Conditions, flow increases associated with clearcut conditions were prorated based on the proportion of a subWAU's or watershed's area associated with both younger and older age classes. The "Entirely Clearcut" simulations were intended to indicate an upper range of potential peakflow increases and assumed that an entire subWAU or watershed had been recently clearcut.

At the beginning of a given simulation, a snowpack water equivalent assumed representative of forested conditions was assigned to each elevation zone (C. Veldhuisen, 1993, Snowpack Prediction Equation for the Nooksack Sub-region, unpublished report) because onsite measurements of snowpack water equivalents in the Acme WAU were not available. For the areas with young forest age classes and recent clearcuts, an additional 38 mm of water equivalent (Connelly and Cundy 1992) was added to each elevation zone to represent the effects of harvesting upon snowpack accumulation. Although these additions are based on the results of recent research in the North Cascades, the representativeness of these adjustments for sites in the Acme WAU is not known. Once a snowpack within a particular elevation zone had been entirely "melted" during a rain-on-snow simulation, moisture from snowmelt was no longer available for runoff.

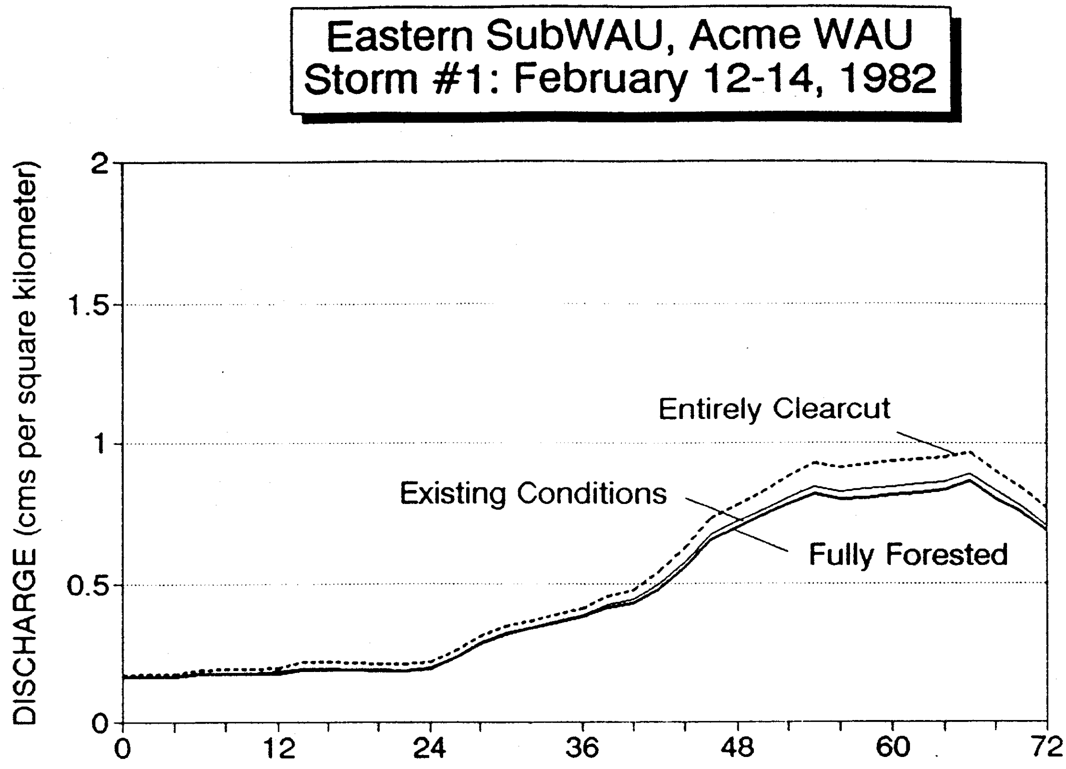
Simulation Results

By combining outflows from each elevation zone, streamflow at the mouth of a subWAU or watershed was determined for each of the five storms. Instantaneous peak discharges generally occurred during the later portion of a storm, supporting the concept that the cumulative effects of antecedent rainfall and snowmelt have an important influence on the magnitude of these flows. Because the emphasis of this analysis is focused on peakflows, simulated streamflows for only the last three days of each storm are shown in Figures 7, 8, and 9.

Results for the Eastern SubWAU, Western SubWAU, and Jones Creek Watershed indicate a range of peakflow responses to the five storms. Peakflows associated with Fully Forested conditions averaged 1.03 cubic meters per second per square kilometer ($m^3s^{-1}km^{-2}$) (range = 0.86-1.25), 1.06 $m^3s^{-1}km^{-2}$ (range = 0.87-1.27), and 1.24 $m^3s^{-1}km^{-2}$ (range = 0.98-1.48), for the Eastern SubWAU, Western SubWAU, and Jones Creek Watershed, respectively. These results indicate a general trend towards higher peakflows with increased watershed elevation.

Simulated peakflows associated with Entirely Clearcut conditions averaged 1.15 $m^3s^{-1}km^{-2}$ (range = 0.93-1.49), 1.28 $m^3s^{-1}km^{-2}$ (range = 1.03-1.49), and 1.56 $m^3s^{-1}km^{-2}$ (range = 1.18-1.77) for the Eastern SubWAU, Western SubWAU, and Jones Creek Watershed, respectively. These peakflows represented an average increase over forested conditions of 11, 20, and 26% (Figure 10). It needs to be emphasized that these increases assume the entire subWAU or watershed has been entirely harvested and that any forest vegetation is $\leq$10 years of age.

In 1991, the Washington Department of Natural Resources, released rain-on-snow guidelines for emergency rule implementation. These guidelines indicated that additional increases in water of 25 to 50 mm (1 to 2 in) during a 24-hour storm event are expected for watersheds in the rain-on-snow zone with a high proportion of their area in young age classes (Department of Natural Resources 1991). An additional 25 mm of water available for runoff (from snowmelt) was assumed to increase the magnitude of a 10-year storm to that of a 50-year storm. Similarly, an additional 50 mm of water available for runoff was assumed to increase the magnitude of a 10-year storm to that of a 100-year storm. The results of the this analysis for the Eastern SubWAU, the Western SubWAU, and the Jones Creek Watershed with 35%, 55% and 85%, respectively, of their areas within the transient snow zone and an assumed



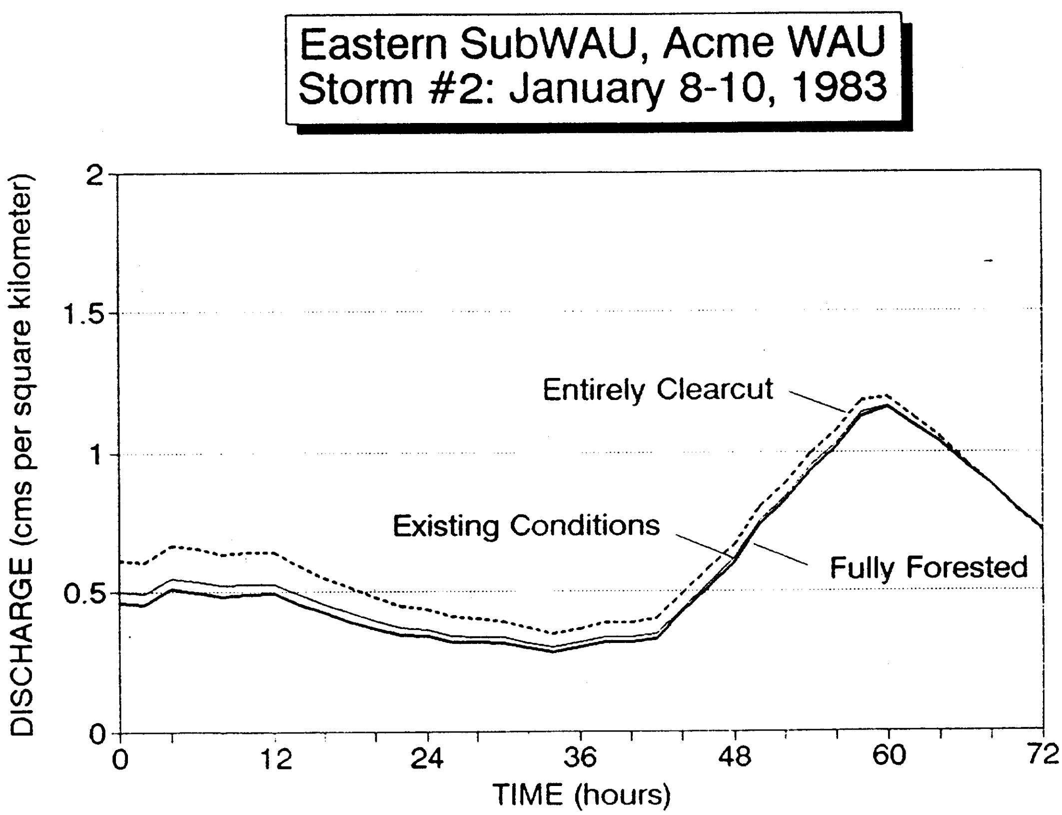
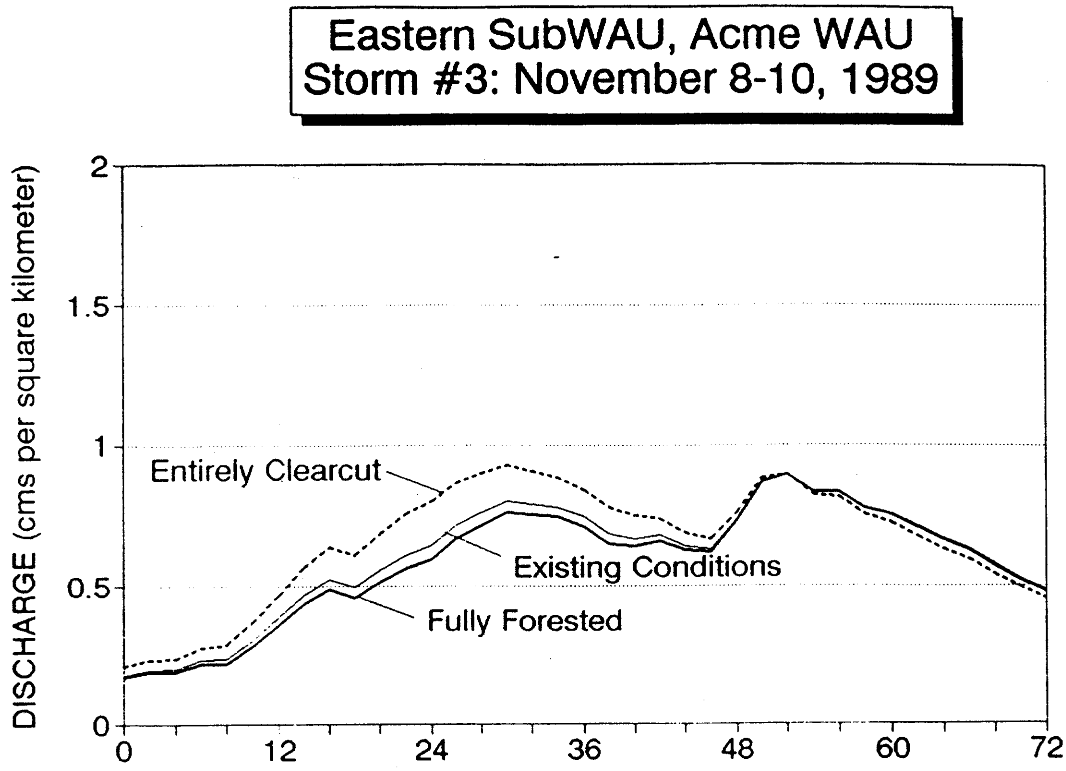
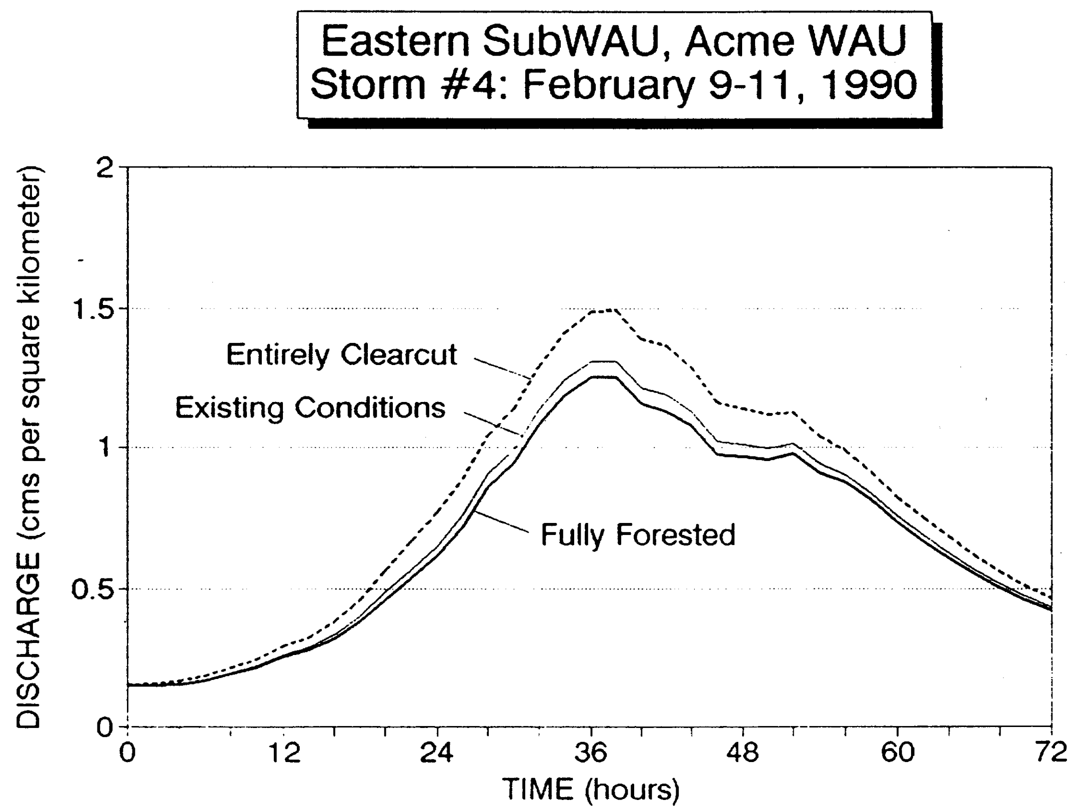


Figure 7 Rain-on-snow hydrograph simulations for Storms #1 through #5, Eastern SubWAU, Acme WAU (Fully Forested = subWAU covered with trees >25 years of age; Existing Conditions = subWAU with current age class distribution; Entirely Clearcut = subWAU covered with trees ≤10 years of age).

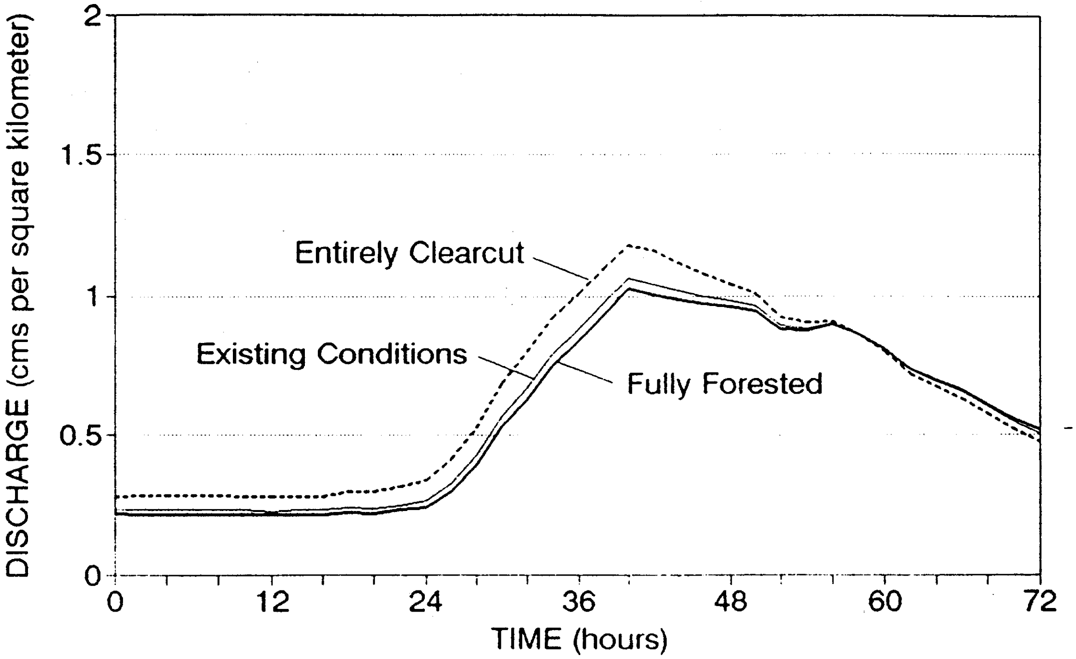


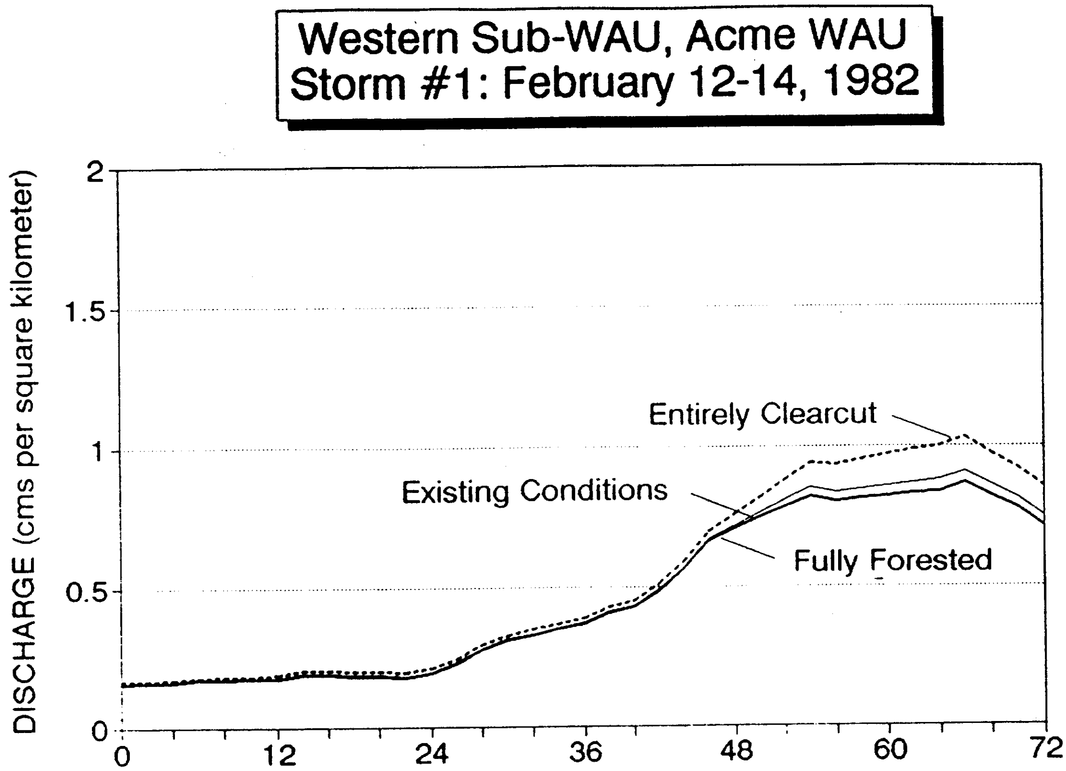
Eastern SubWAU, Acme WAU
Storm #3: November 8-10, 1989
DISCHARGE (cms per square kilometer)
2
1.5
1
0.5
0
Entirely Clearcut
Existing Conditions
Fully Forested
0
12
24
36
48
60
72



Eastern SubWAU, Acme WAU
Storm #4: February 9-11, 1990
DISCHARGE (cms per square kilometer)
2
1.5
1
0.5
0
Entirely Clearcut
Existing Conditions
Fully Forested
0
12
24
36
48
60
72
TIME (hours)

Eastern SubWAU, Acme WAU
Storm #5: November 8-10, 1990





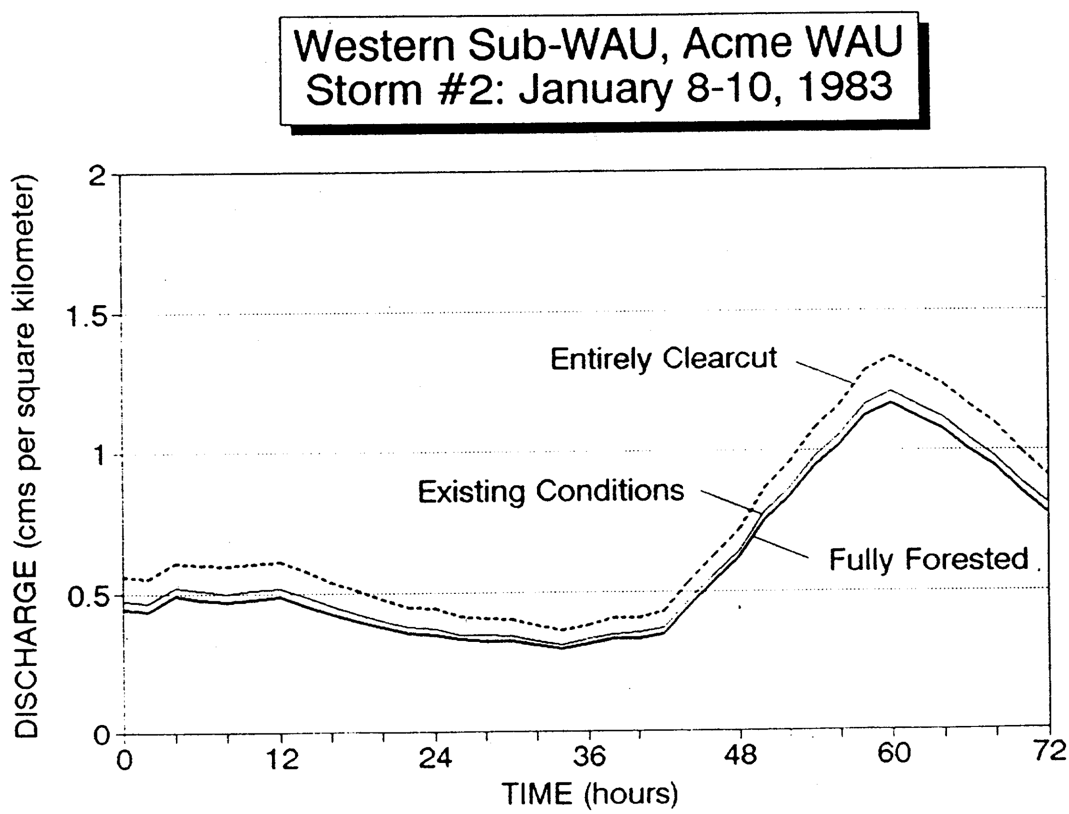
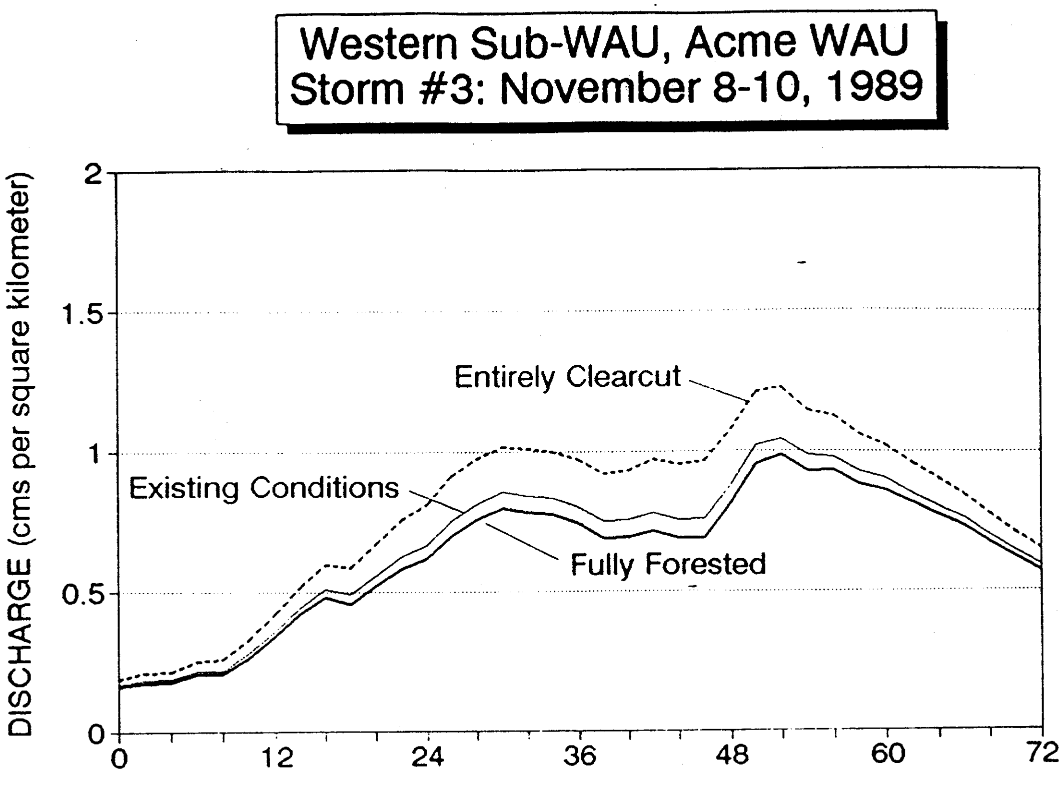
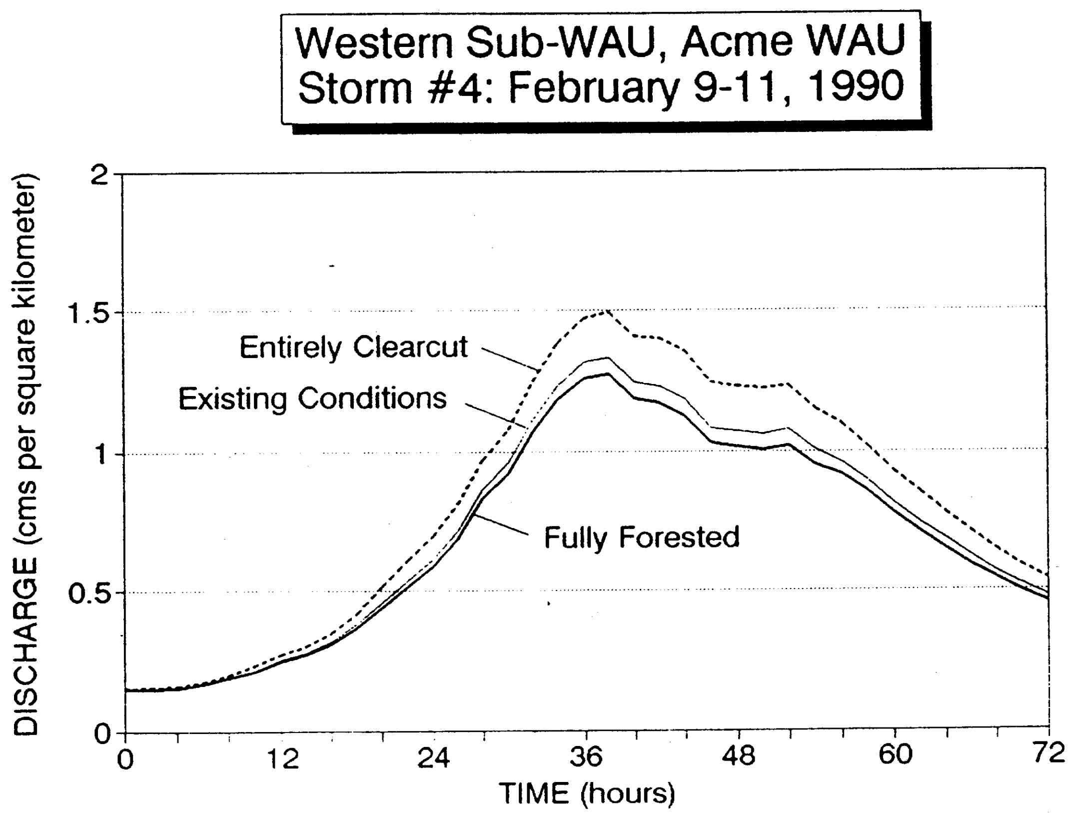
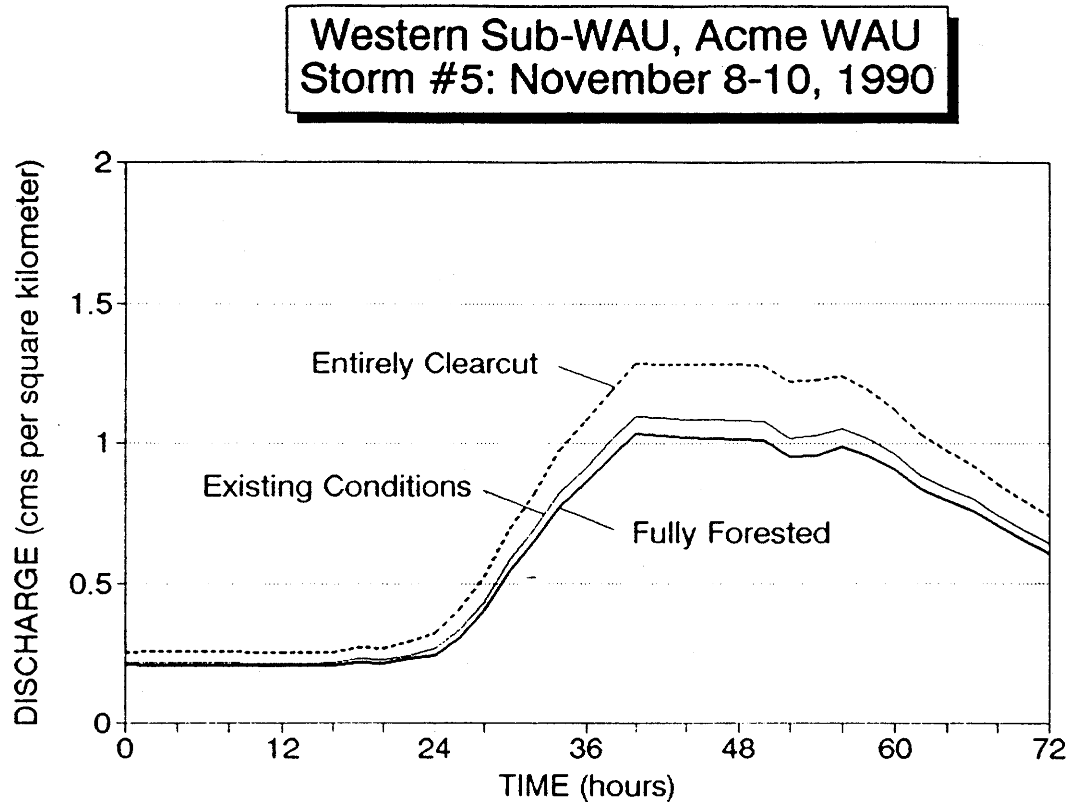


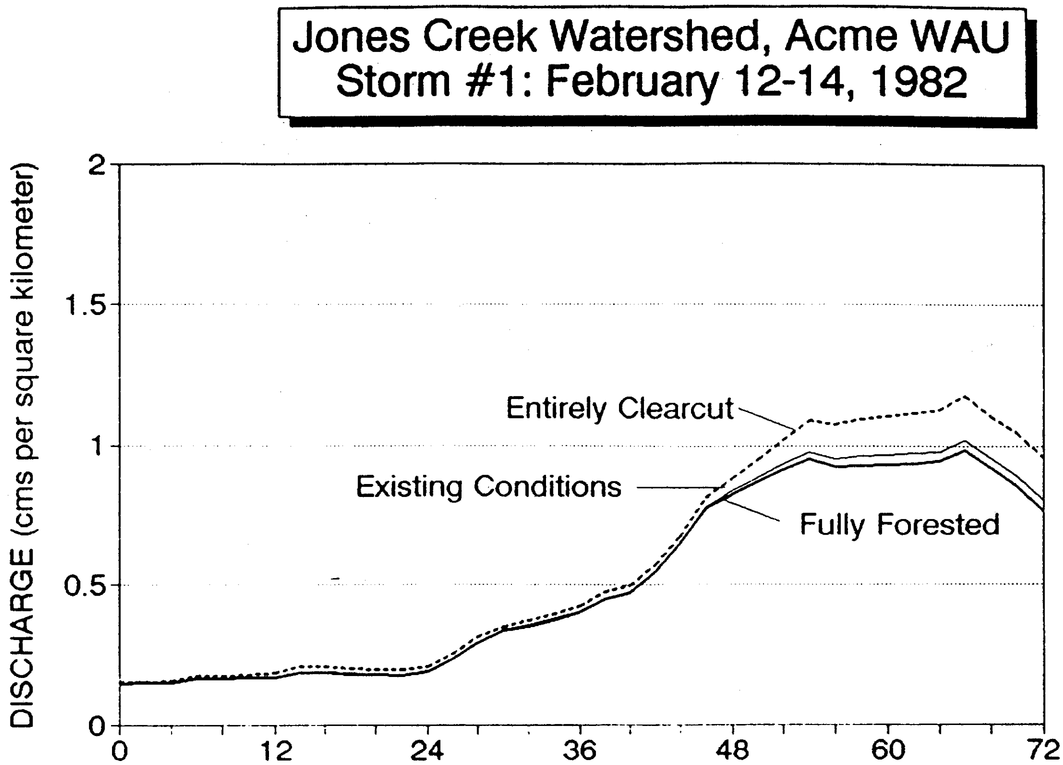
Figure 8 Rain-on-snow hydrograph simulations for Storms #1 through #5, Western SubWAU, Acme WAU (Fully Forested = subWAU covered with trees >25 years of age; Existing Conditions = subWAU with current age class distribution; Entirely Clearcut = subWAU covered with trees ≤10 years of age).


Western Sub-WAU, Acme WAU
Storm #3: November 8-10, 1989
DISCHARGE (cms per square kilometer)
2
1.5
1
0.5
0
0
12
24
36
48
60
72
Entirely Clearcut
Existing Conditions
Fully Forested


Western Sub-WAU, Acme WAU
Storm #4: February 9-11, 1990
DISCHARGE (cms per square kilometer)
2
1.5
1
0.5
0
0
12
24
36
48
60
72
TIME (hours)
Entirely Clearcut
Existing Conditions
Fully Forested



Western Sub-WAU, Acme WAU
Storm #5: November 8-10, 1990
Entirely Clearcut
Existing Conditions
Fully Forested
DISCHARGE (cms per square kilometer)
TIME (hours)
0
0.5
1
1.5
2
0
12
24
36
48
60
72



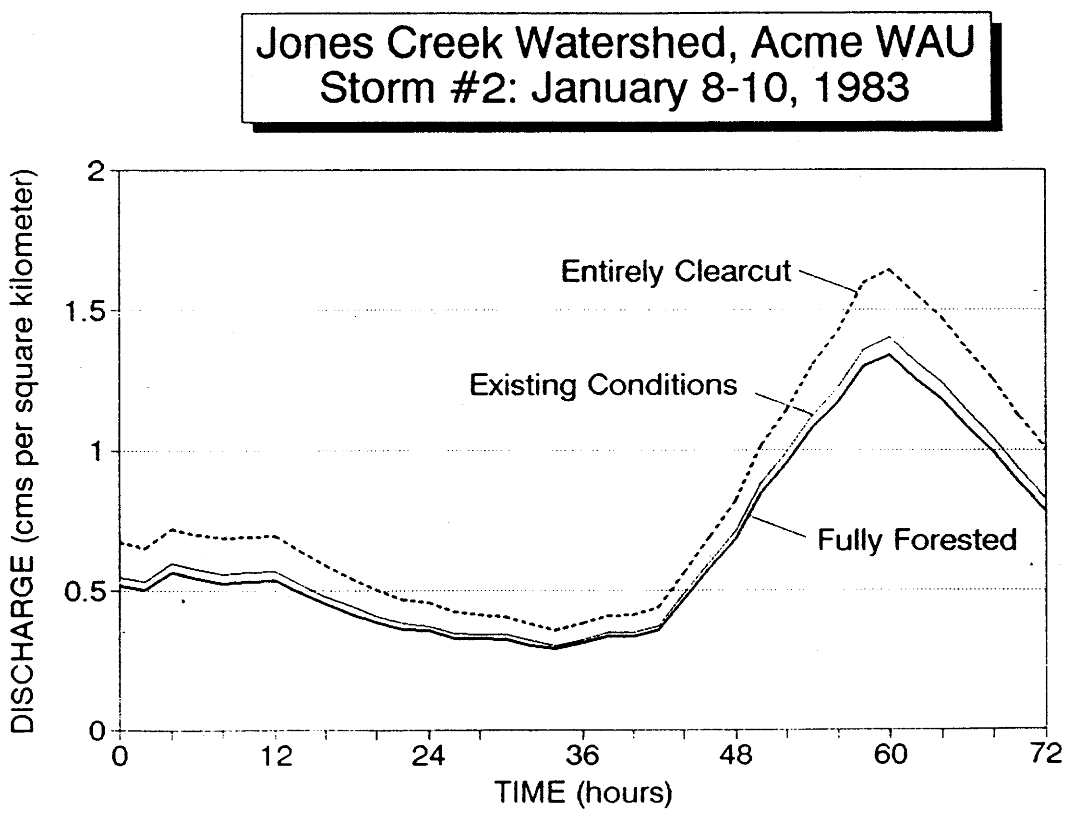
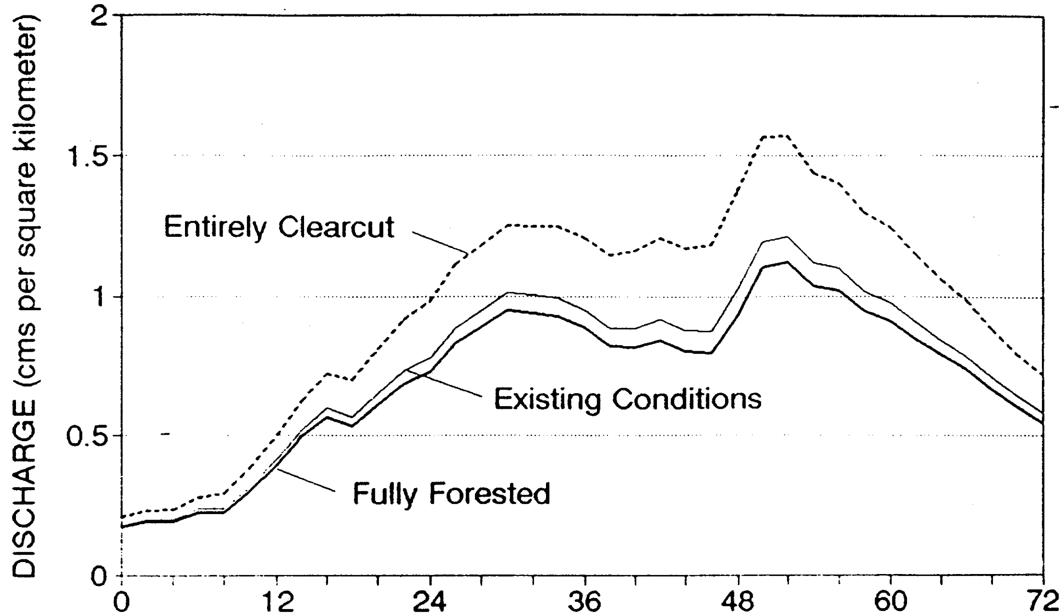
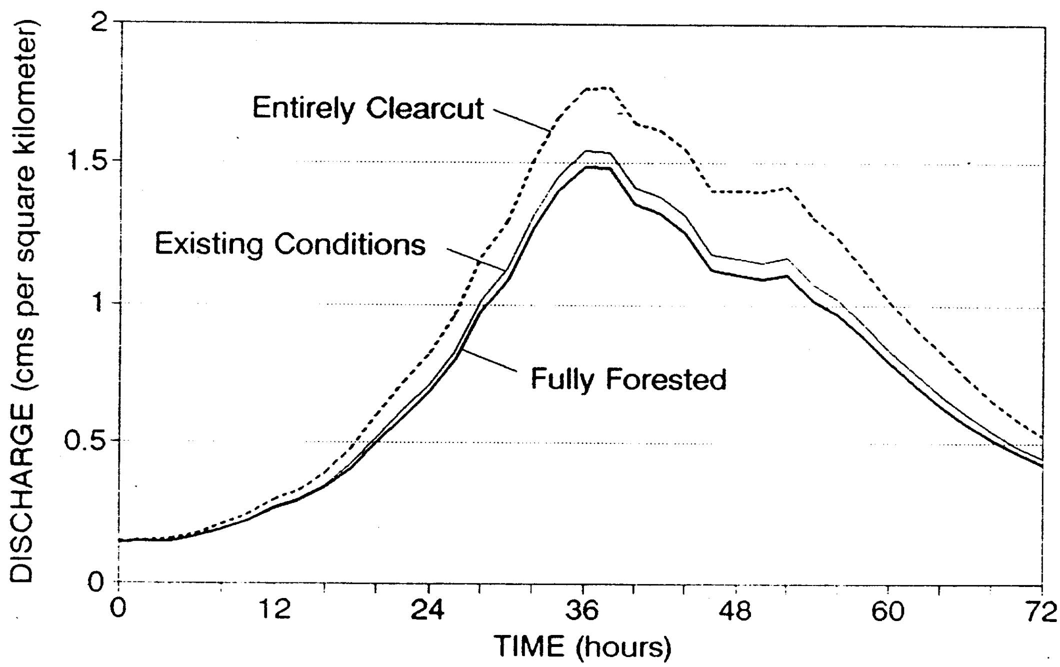


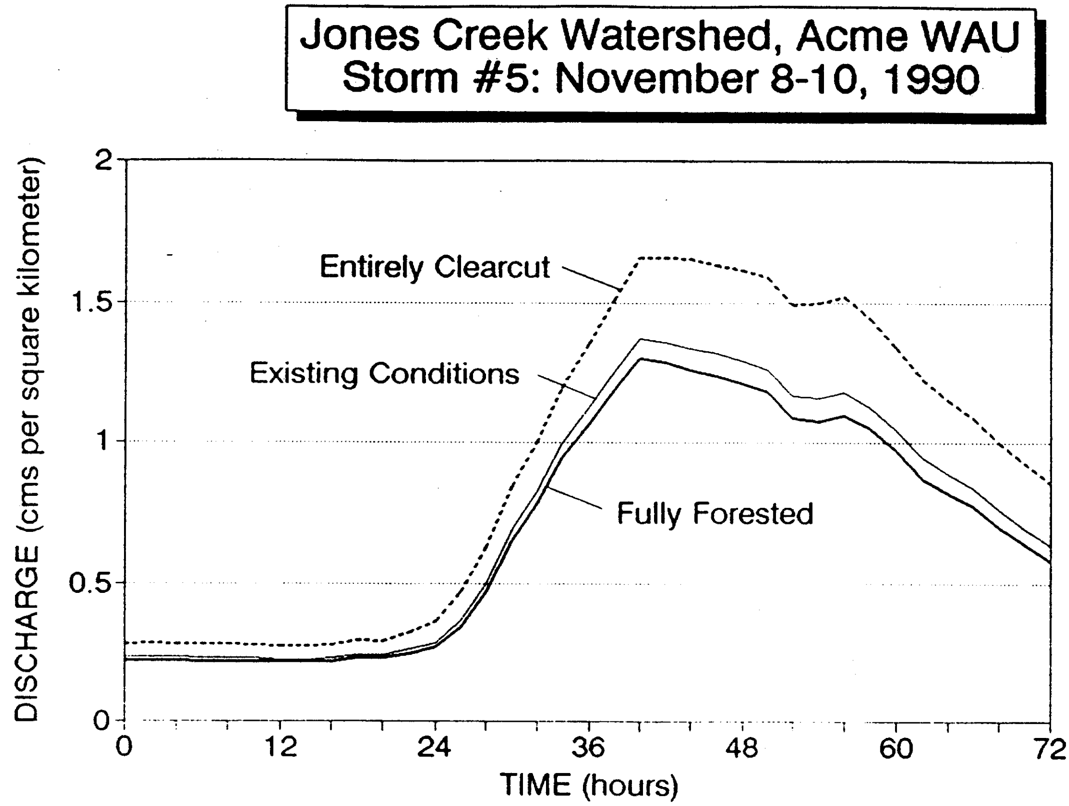
Figure 9 **Rain-on-snow hydrograph simulations for Storms #1 through #5, Jones Creek Watershed, Acme WAU (Fully Forested = subWAU covered with trees >25 years of age; Existing Conditions = subWAU with current age class distribution; Entirely Clearcut = subWAU covered with trees ≤10 years of age).**

Jones Creek Watershed, Acme WAU
Storm #3: November 8-10,1989



Jones Creek Watershed, Acme WAU
Storm #4: February 9-11, 1990




Jones Creek Watershed, Acme WAU
Storm #5: November 8-10, 1990
Entirely Clearcut
Existing Conditions
Fully Forested
DISCHARGE (cms per square kilometer)
TIME (hours)
0
0.5
1
1.5
2
0
12
24
36
48
60
72

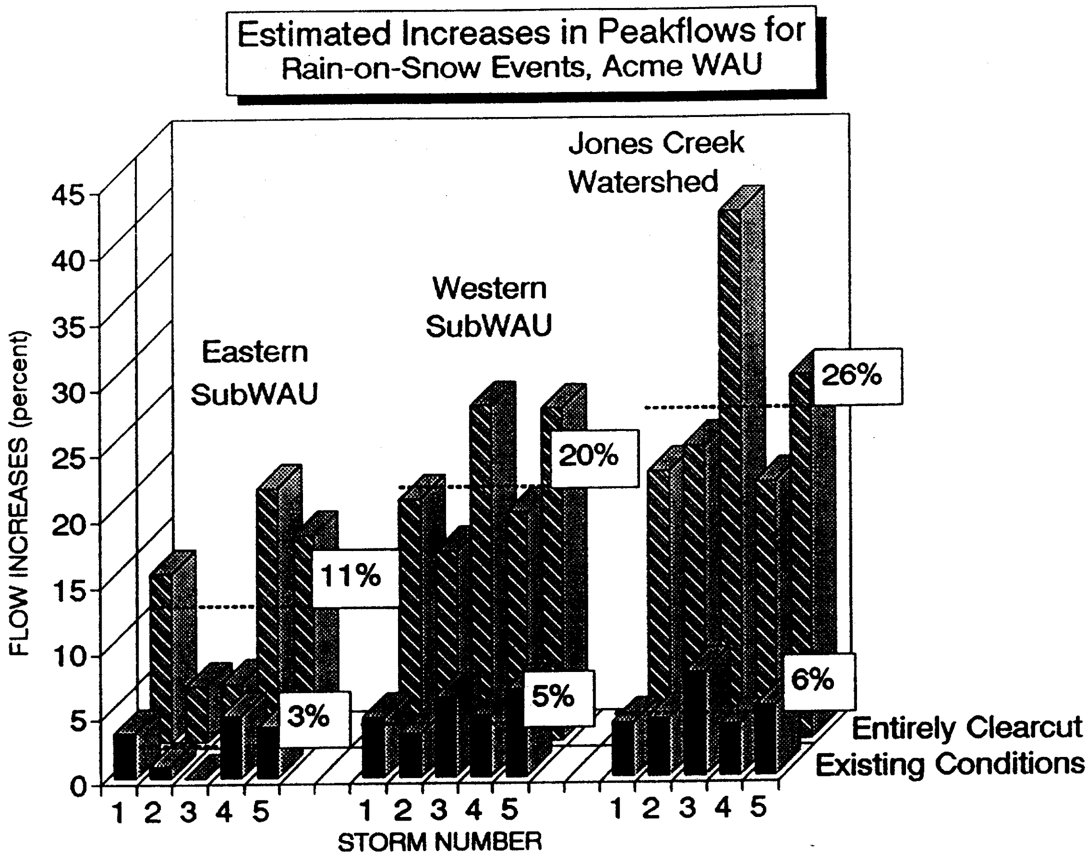


Figure 10 Summary of rain-on-snow peakflow increases for the Eastern SubWAU, Western SubWAU, and Jones Creek Watershed (Note: Solid bars and striped bars denote increases associated with Existing Conditions and Entirely Clearcut Conditions, respectively, in comparison to Fully Forested watersheds).

additional 38 mm of snowpack water equivalent due to harvesting effects, show a considerably smaller magnitude response of peakflows to harvesting.

For Entirely Clearcut conditions, the relative change in recurrence interval represented by the estimated increases in peakflows can be approximated by comparing them to peakflows from gaged watersheds in the western Cascades. Two watersheds, i.e., Lake Creek and Skookum Creek, were selected for this analysis. The period of record for each of these gages is approximately 20 years and they were jointly used to develop a common "discharge vs recurrence interval" relationship (Figure 11). Based on this relationship and the Entirely Clearcut simulation results for rain-on-snow peakflows, the magnitude of a 10-year peakflow would be increased to approximately that of a 14-, 20-, and 24-year event for the Eastern SubWAU, the Western SubWAU, and the Jones Creek Watershed, respectively (Figure 11).

The proportion of area occupied by young forest age classes represents an important variable with regard to rain-on-snow effects associated with timber harvesting. Following harvesting, the establishment and growth of trees begins to reduce the potential for accelerated rain-on-snow melt in clearcut openings. As the height and canopy cover of establishing forest vegetation increases, the potential for increased snowpack accumulation and accelerated snowmelt are decreased. An example of a relationship between "hydrologic recovery" and stand age is illustrated in Figure 12. This figure indicates little hydrologic recovery occurs for the first 10 years following harvest but that it occurs relatively rapidly over the next 15 years.

Although the relationship shown in Figure 12 was developed for the western Oregon Cascades, it never-the-less represents the general trend in hydrologic recovery expected for western Washington forests. Full "hydrologic recovery" of rain-on-snow effects is generally expected for areas occupied by forest stands greater than 25 years of age (Department of Natural Resources, 1991).

Where only portions of the Acme WAU were occupied by relatively young forest age classes, expected peakflow increases from a subWAU or watershed would be considerably less than those shown for clearcut conditions. The general distribution of age classes for portions of the Acme WAU is shown in Table 4. As of late 1994, 23% or less of the SubWAUs was occupied by forest stands of $\leq$10 years of age. Assuming those areas with forest age classes of $\leq$10 years cause an increase equivalent to that of clearcut conditions and stands between 11 and 26 years proportionately less (as indicated by Figure 12), the simulated peakflows for the Eastern SubWAU, Western SubWAU, and Jones Creek Watershed averaged 1.06 $m^3s^{-1}km^{-2}$ (range = 0.89-1.31), 1.12 $m^3s^{-1}km^{-2}$ (range = 0.91-1.33), and 1.31 $m^3s^{-1}km^{-2}$ (range = 1.02-1.54), respectively. On average, these flows represent an increase of 3 to 6% above that for Fully Forested conditions (Figure 10).

Comparing estimated increases of 3 to 6% with the discharge vs recurrence interval relationship for the Lake Creek and Skookum Creek watersheds indicates that these

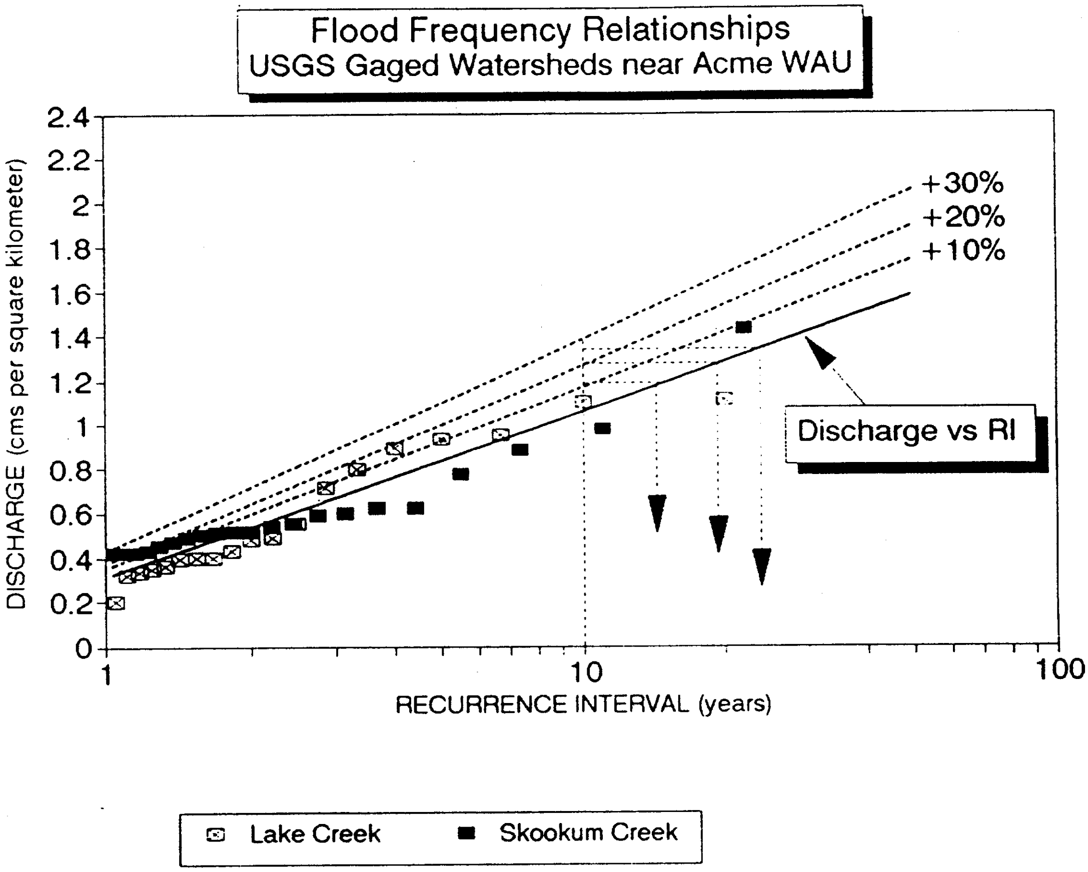


Figure 11 Peak discharge versus recurrence interval (RI) for Lake Creek and Skookum Creek (Williams and Pearson 1985).

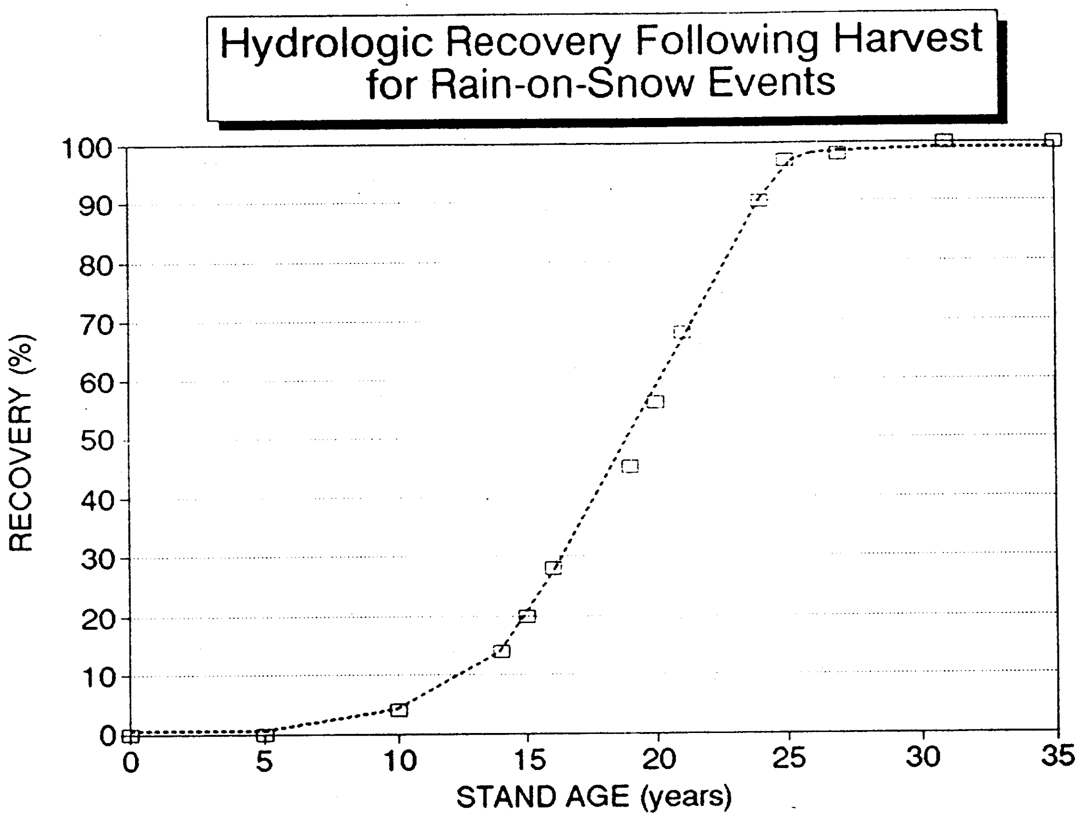


Figure 12 Hydrologic recovery of increased snowmelt associated with rain-on-snow events in comparison to stand age, western Cascades of Oregon.

Table 4 Percent of area in indicated forest age classes for portions of the Acme WAU as of 1994 (Note: Because age classes were obtained largely from interpretation of aerial photo imagery with some in-the-field verification, the exact age-class distribution of younger stands is not known. However, given the general level of modeling capability for rain-on-snow simulations, a more refined estimate of age-class distributions is not warranted).

	Percent of Area		
Forest Age Class (years)	Eastern SubWAU	Western SubWAU	Jones Ck. Watershed
0-10	22	16	23
11-26	13	21	0
27+	65	63	77

increases in flow would increase the magnitude of a 10 year event to that of approximately a 12 year event, or less. Given the wide range in annual peakflows experienced by mountain streams (the coefficient of variation in annual peakflows is nearly $\pm$20% for the South Fork Nooksack River) and considering the potential for inaccuracies in meteorological estimates, simulation processes, and measured streamflows, a simulated 3 to 6% increase in peakflows for existing conditions would be exceptionally difficult to detect for any tributary streams within the Acme WAU. In addition, given the steep gradients and coarse substrates typical of channels in the Eastern and Western SubWAUs, a 3 to 6% increase in peakflows is not expected to be a significant factor causing channel instabilities within the SubWAUs. However, if unconstrained stream reaches have previously become destabilized via landslides, dam-break floods, harvesting along streambanks, road drainage, or some other mechanism, increased flows may contribute unstable conditions.

The large natural variability of hydrologic processes, particularly those associated with large storm events, makes it difficult to develop definitive conclusions regarding how specific management practices affect runoff patterns or the stability of hillslopes and stream systems. However, several direct and indirect effects may potentially be associated with the additional snowmelt water from watershed areas occupied by young forest age classes (i.e., $\leq$25 years). For shallow soils on steep slopes, an increase in the amount of moisture available to watershed soils during large storms (e.g., a 11-26% increase in local peakflows were simulated for clearcut conditions) could contribute to a reduction in the factor of safety because of increased pore pressures. For deep-seated types of mass soil movements, the combined effects of reduced transpiration loss following forest harvesting and incremental increases in soil water during large storms might also augment the downslope movement of soil and weathered materials. In other instances, road drainage may be affected. For example, a 11 to 26% increase in peakflows from clearcut areas may be of sufficient magnitude to require increased culvert sizing at stream crossings.

The potential for increases in water availability and peakflows to affect slope erosion process and channel stability are most likely to occur within or close to a harvest unit. Farther downstream, the potential effects of increased flows are likely to become less significant.

CONCLUSIONS

This analysis of rain-on-snow hydrology for large winter storms associated with the Acme WAU indicates the following:

- During rain-on-snow conditions, rainfall provides the major source of moisture available to forest soils and stream systems.

- Depending upon location within the WAU, a 11 to 26% average increase in peakflows was projected for clearcut conditions. For slopes with high erosion hazard, increased amounts of moisture delivered to the soils during rain-on-snow conditions as a result of clearcut harvesting may contribute to local slope instability and increased landslide frequency. This additional water should be considered with other onsite factors, such as the routing of water by road drainage systems and the loss of root strength following harvesting or burning, in assessing the relative stability of specific slopes.

- For areas that currently have, or will have in the future, a high percentage of area in younger age classes (i.e., $\leq$25-years old), an increased design capacity of approximately 10 and 20% for the Eastern and Western SubWAUs, respectively, should be considered for culverts and other drainage structures. For the Jones Creek Watershed, increased design capacities of 25% are recommended.

- The relative increase in rain-on-snow peakflows associated with simulations of clearcut harvesting (this analysis) are considerably smaller in magnitude than the regional increases projected by the Department of Natural Resources (1991).

- Subdrainages within the Acme WAU currently have approximately 16 to 23% of their area in forest age classes $\leq$25-years old. Rain-on-snow simulations for five large storm events indicates that accelerated snowmelt associated with current watershed conditions could potentially increase peakflows by an average of 3 to 6%.

- Based on a frequency analysis of annual peakflows for two gaged watersheds, a 3 to 6% increase in peakflows would increase the magnitude of a 10-year event to that of a 12-year event, or less.

- An approximate 3 to 6% average increase in peakflows during rain-on-snow conditions indicates that flow increases along Acme are unlikely to be a major cause of initiating channel instability. However, where unconstrained channel reaches have become impacted by other events (landslides, dam-break floods, etc.) flow increases may contribute to maintaining an unstable condition.

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APPENDIX 5-2

TO: Jeff Grizzel

FROM: Bob Beschta
Curt Veldhuisen

SUBJECT: Response to Peer Review dated February 19, 1997
Hydrologic Change Module - Acme Watershed Analysis

DATE: July 11, 1997

The following are responses to specific items listed in the peer review for the Acme Hydrology module. Each response comment is preceded by a paraphrased summary of your request in bold.

Item #1: Figure 5-6 should be provided at a 1:24,000 scale with the standard map label, "Map C-2".

The revised version of Figure 5-6 with an additional label is enclosed.

Item #2: Figure 5-1 provides some, but not all elements of required Map C-2.

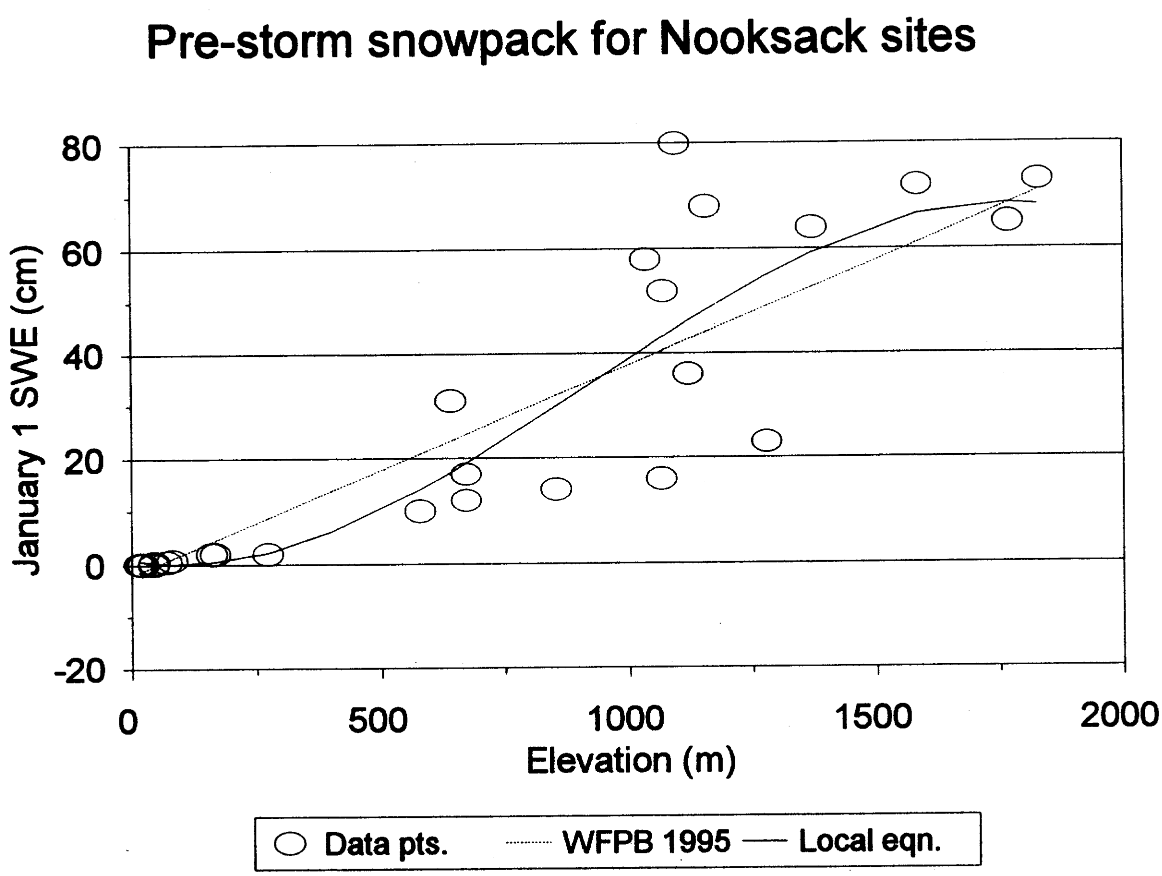
The location of hydrologic assessment areas are shown in Figure 5-6, if not in Figure 5-1. Elevation zone boundaries used for hydrologic modelling have been added as well, so that Figure 5-6 provides the equivalent information to Map C-1 as well as C-2. Following your approval of the contents, a copy of Figure 5-6 will be submitted at a 1:24,000 scale.

Item #3: A table listing acreages of cover type by elevation band (equivalent to Form C-1) is not provided.

Acreages of forest age classes in each assessment unit is provided in Table 5-1 (page 5-11). This data was used to develop estimates of flow increases for current forest cover by interpolation between modelled fully forested and fully immature scenarios. Using this method, subdivision of cover acreage by elevation zone was not needed for this analysis. Although in past analyses both analysts (Beschta and Veldhuisen) have used cover data subdivided by elevation for rain-on-snow modelling, this step was discontinued because (a) it was a major data-collection effort (b) it had essentially no effect on the results, and (c) it quickly becomes out-of-date as further logging/recovery occurs in the WAU.

Item #4: Details on the alternative relationship between pre-storm snow water equivalent and elevation are not provided.

A graph of this relationship is provided in the supplemental figure which follows:



Supplemental Figure. January 1 snowpack (snow water equivalent) and snow course elevation used to estimate pre-storm conditions for Acme rain-on-snow modelling. Data points (circles) represent single station averages from 27 monitoring sites in the Nooksack basin or nearby. Lines represent: 1) first-order regression for "North Cascades" region provided in the Manual (i.e. WFPB 1995) and 2) third-order regression developed for local stations. The local equation was used for modelling.

Item #5: The report does not adequately justify the rationale for using lysimeter data for adjusting pre-storm snowpack between cover types.

Bob Beschta provides the following justification:

For purposes of simulating rain-on-snow conditions, an estimate of the differential snowpack water equivalent between forested areas and clearcuts was needed. Such data are normally unavailable on a given WAU. Thus, snowmelt lysimeter research by Connelly and Cundy (1992) was used to obtain such an estimate. Their results provided measurements of the combined rainfall and snowmelt outflow from the bottom of the snowpack during rain-on-snow conditions for (1) forest conditions and (2) clearcut conditions.

Snowpack outflows, as measured by lysimeters, should provide a reasonable approximation of snowpack water equivalent because:

(a) The amount of rainfall onto the forested snowpack and the clearcut snowpack should be the same. Canopy interception is quickly attained during a large rainfall event and thus there should be essentially no difference between the two sites.

(b) Although the forested site and the clearcut site may experience differing wind patterns during a major rainfall event, the air temperatures and relative humidities should be similar. The net result of these conditions is that while they may influence the 'rate of snowmelt' at each site, they are not likely to significantly affect the amount of total moisture outflow at the bottom of the snowpack. Each mm of condensation is able to melt 7.5 mm of snowpack water equivalent for an isothermal snowpack at 0 degrees Celsius. Because clearcuts are likely to have greater condensation melt (due to greater exposure to wind), the 38 mm differential measured from the Connelly and Cundy study (and which was used in the rain-on-snow simulations) should probably be decreased somewhat (because a greater portion of the outflow at the bottom of the clearcut snowpack would likely be attributed to condensation melt). However, the amount of adjustment to account for differing quantities of condensation melt for the two sites is to be small. Furthermore, without additional information regarding meteorological conditions for the Connelly and Cundy study sites, such a reduction would be arbitrary.

As a result of (a) and (b), the major remaining factor affecting total snowmelt outflow at the bottom of a snowpack is the amount of initial snowpack water equivalent. It was for this reason that the results of Connelly and Cundy (1992), which represented actual field measurements of moisture outflow at the bottom of snowpacks for forest and clearcut conditions in the Washington Cascades, were utilized in the rain-on-snow simulations.

It should also be noted (and was indicated on page 5-6 of the module report) that the 38 mm of differential outflow between the forest and clearcut conditions exceeded "...measured differences between the amounts in an opening versus those under a forest canopy for approximately 80 percent of the rain-on-snow events reported by Connelly and Cundy (1992)." Thus, the adjustment the snowpack water equivalent that was used in the simulations likely represents "above average" effects of harvesting.

Item #6: A summary table of peakflow estimates is requested for each storm simulation by sub-basin.

The supplemental table provides the requested information.

Items #7 & 8: An explicit statement of peak flow sensitivity (hazard) ratings is requested. Further discussion of the role of peakflows on mass wasting is requested.

For the "existing forest" conditions within the Acme WAU, increases in peakflows of 3 to 6% were projected where mountain streams meet the South Fork Nooksack floodplain. This relatively small percentage increase in peakflows, and the fact that mass wasting processes are of considerably greater significance to channel changes results in Low hazard ratings for forestry-related enhancement of rain-on-snow peakflows.

The potential for greater increases with future harvest activity can be evaluated from the results of fully clearcut scenarios. For Van Zandt Dike (i.e. east-side) tributaries, potential flow increases are modest, averaging 11% for a fully immature conditions. For Stewart Mountain tributaries, flow increases averaging 20-26% (for west-side and Jones Creek) are projected for maximum immaturity indicating greater potential response. The likelihood of a given basin undergoing sufficient harvest to produce substantially larger flow increases than current conditions (e.g. 10-26%) depends on several unknown factors. These uncertainties include: (1) the proportion of timbered areas included in leave areas for riparian and slope stability functions, (2) the proportion of the basin in mature timber at the time, and (3) harvest plans, access and other economic factors.

It is also difficult to predict channel response to larger flow increases, though west-side tributaries are not likely to be very sensitive. The upper channels (upstream of alluvial fan areas) are quite steep and sediment transport is controlled by inputs from mass wasting and availability of in-channel storage features, rather than flow rates. Channel beds and banks are normally resistant to scour, being composed of bedrock or armored with boulders and woody debris; an example of this situation in Jones Creek is shown in Figure 5-7, part c. Past evidence of major channel disturbance has been primarily related to debris flows and/or dam-break floods, rather than simply high flows (see Section 6.4.4). Although the major channel response in lower tributary reaches (i.e. alluvial fans and downstream segments) occur primarily in response to sediment inputs as well, elevated peakflows could

Supplemental Table. Summary of peakflow responses for individual simulations of rain-on-snow events (see more detailed description in the Hydrologic Change Assessment of the Acme WAU).

Hydrologic Unit	Storm Number	Forest Conditions ($m^3/s/km^2$)	Existing Conditions ($m^3/s/km^2$)	Clearcut Conditions ($m^3/s/km^2$)
Eastern SubWAU	1	0.86	0.89	0.97
	2	1.15	1.16	1.20
	3	0.89	0.89	0.93
	4	1.25	1.31	1.49
	5	1.02	1.06	1.18
Western SubWAU	1	0.87	0.91	1.03
	2	1.17	1.21	1.34
	3	0.98	1.04	1.23
	4	1.27	1.33	1.49
	5	1.03	1.10	1.29
Jones Creek	1	0.98	1.02	1.18
	2	1.34	1.40	1.64
	3	1.12	1.21	1.57
	4	1.48	1.54	1.77
	5	1.30	1.37	1.66
5-STORM AVERAGES				
Eastern SubWAU		1.03	1.06	1.15
Western SubWAU		1.06	1.12	1.28
Jones Creek		1.24	1.31	1.56

accelerate incision into fresh deposits. Once channels have incised into such deposits, beds return to a coarse-textured condition and provide abundant channel capacity to prevent overbank flows from rain-on-snow increases. Examples of flow capacities on the Jones, Hardscrabble and Sygitowicz fans are shown in Figure 5-7, part b, d, & e.

Rain-on-snow enhancement in logged areas can increase soil moisture inputs which, in turn, can contribute to mass wasting initiation in marginally stable areas. This influence is acknowledged as a potential contributor (among others) to the initiation of mass wasting and was considered in prescriptions (see Causal Mechanism and Prescription Report #1).

To conclude, items #1&2 will be resolved by submitting the revised version of Figure 5-6 at the larger scale. The responses contained here will be attached to the existing report as an addendum. Please contact Curt Veldhuisen at (360) 671-4787 if there are any further questions.